ERROR ANALYSIS OF THE MARK 86 GUN CONTROL SYSTEM

Charles Albert Hoffer

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Monterey, California

THESIS

Error Analysis
of the
Mark 86 Gun Fire Control System (U)

by

Charles Albert Hoffer

June 1974

Thesis Advisor: John R. Ward

[redacted]

This document contains 48 pages.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Error Analysis of the Mark 86 Gun Fire Control System (U)		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; June 1974
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles Albert Hoffer		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE JUNE 1974
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) CONFIDENTIAL
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16.

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Mark Eighty-Six Gun Fire Control System was designed by Lockheed Electronics Company to take range, bearing and elevation inputs from either the radar receiver, target designation transmitters (TDT), or a closed circuit television system aboard ship in order to solve the air, surface and gunfire support problems. The solution to the fire control problem is in terms of computed gun and fuze orders.

The MK 86 GFCS operates digitally and is currently designed to operate with 5"/54 gun mounts. However, it could be adapted to almost any naval gun.

This thesis is directed towards the development of a system error analysis, based on the USS Norton Sound (AVM-1) test data provided by NSMSES.

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(Page 1) S/N 0102-014-6601

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Error Analysis
of the
Mark 86 Gun Fire Control System (U)

by

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Submitted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

June 1974

ABSTRACT

The Mark Eighty-Six Gun Fire Control System was designed by Lockheed Electronics Company to take range, bearing and elevation inputs from either the radar receiver, target designation transmitters (TDT), or a closed circuit television system aboard ship in order to solve the air, surface and gunfire support problems. The solution to the fire control problem is in terms of computed gun and fuze orders.

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I BACKGROUND

Since the MK 86 GFCS is the United States Navy's first digital fire control system, and since unique opportunities exist at the Naval Postgraduate School to study such a system, three professors at the School, D. E. KIRK, H. A. TITUS and J. R. WARD, have formed a group to study the accuracy of air target tracking and ballistics computation with special reference to the effectiveness of the system's three-dimensional digital filter.

The three functions of the system's computer which are relevant here are the AA Track Data-Processing Program, the Ballistics Program and the Gun Orders Operation Program.

A. AA TRACK DATA-PROCESSING PROGRAM

The AA Track Data-Processing Program provides the numerical digital filtering of the 3-D target data supplied by the AN/SPG-60 Radar. It performs the appropriate coordinate conversions, parallax corrections, etc., and provides filtered target position and velocity data to the Ballistics Program. The basic data rate is four hertz.

B. BALLISTICS PROGRAM

The Ballistics Program computes inertial gun orders and associated fuze time at a two-hertz rate for the Gun Order Processing Program. This program determines, among other things, lead angles, staleness compensation, two-hertz gun orders and fuze time, and the predicted projectile impact point in range, bearing and elevation.

C. GUN ORDER OPERATION PROGRAM

The Gun Order Operation Program provides the data-processing and logical control for all the functions required between the ballistics output and the final development of fuze and gun orders. In particular, this program performs the conversion of gun orders to deck coordinates for use at the gun mounts and interpolates the inertial gun order data to a higher rate (64 hertz).

II. OVERVIEW OF DATA ANALYSIS

(U) The major sources of non-ballistic error in a digital gun fire control system would normally be expected in the radar system, the servo systems, the battery alignment and possibly in the computer operations. Of these, it was anticipated that the major errors in the Mk 86 system would be due to the gun mount servos and to limitations of the 3-D filter. This thesis, therefore, concentrated on these areas.

A. GUN MOUNT SERVOS

(C) Data from the Norton Sound tests, under smooth sea conditions and limited target maneuvers, showed negligible errors in this area.

B. POSITION DATA SMOOTHING

(C) No wild points were noted in the smoothing of the radar measurement data, indicating consistent, low-noise operation at least.

C. VELOCITY ESTIMATION

(C) The filter's estimates of velocity can be considerably in error when the target maneuvers. Much of this error is due to time lags of as much as four seconds in the velocity estimates. This error can cause miss-distances of the order of seventy percent of those observed in the Norton Sound tests.

D. SYSTEM EFFECTIVENESS

(C) To determine the overall effectiveness of the system, an average hit probability and two effectiveness measures were calculated. These

show that even small maneuvers by medium-speed targets can cause a considerable reduction of system effectiveness - due, primarily, to errors in the estimation of target velocity.

III. ANALYSIS OF SYSTEM ERRORS

(U) Since no absolute measurements of target position were provided in the test data furnished by NSMSES, no comparison of the radar measurements with the actual target location can be made. Therefore, the filtered radar measurements will be assumed to yield the actual target position. Further, the analysis will assume perfect projectile ballistics and error-free ballistics calculations in the MK 86 system.

(U) Computations and comparisons for slow and medium-speed targets only will appear in this thesis due to the unavailability of high-speed target data.

(U) A non-maneuvering target will be a target which has an accelaration of less than one-tenth g in any of the X-, Y- or Z- directions.

(U) Table I lists the various runs used in the following analyses. Henceforward they will be referred to by the run number in this table.

The data words are defined in Ref. 1.

A. EFFECTIVENESS OF POSITION DATA SMOOTHING

(C) To check the effectiveness of the 3-D digital filter in smoothing the radar measurement data, a fourth-degree least squares polynomial curve was fitted to the pre-filter measurements of range (VISA01+2), bearing (ABITRU) and elevation (AEISAV). This was done for both a slow-speed, non-maneuvering target (TDU), and a medium-speed, maneuvering target (BQM). These curves were then compared to the filtered range, bearing and elevation (AARNGE, ABIR and AEI) and the differences plotted.

(U) Runs 18 and 20 were selected for the maneuvering target and runs

11 and 12 were selected for the non-maneuvering target. Figures 1 and 2 show sample comparisons for the BQM bearing position data and the TDU elevation position data respectively.

(C) These figures show that, although some small differences exist between the curve-fit position data and the MK 86 filtered position data, the differences are small. This suggests that the filter effectively filters the radar measurement data.

B. FILTER VELOCITY ESTIMATES

(C) The accuracy of the filter's estimates of target velocity in each of the X-, Y- and Z- directions was determined by comparing the filtered velocities ZDOTN ($\dot{Z}$), ZDOTN+1 ($\dot{X}$) and ZDOTN+2 ($\dot{Y}$) with the (approximate) target velocities in the same directions. The latter were obtained by plotting each of the filtered target position coordinates against time and reading off the corresponding slopes.

(C) Figures 3 and 4 show sample comparisons of the target velocity and the system's velocity estimates for runs 11 and 19. The maximum velocity error of twenty yards per second in the Y-direction for run 19 (Figure 3) corresponds to a miss-distance of fifty yards with a typical time of flight of two and one-half seconds.

(C) In addition, these figures show that there is a definite time lag (up to four seconds) before the systems's velocity estimates catch up to a target maneuver.

C. GUN MOUNT FOLLOWING ERRORS

(C) The gun mount following error is the error between the ordered gun position and the gun position repeatback. This error was determined

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by subtracting the actual gun orders, BDG and EDG, from the repeatback quantities, BDGIN and EDGIN.

Run 13 from Table I was selected for this check.

(C) The mean of the difference in train was determined to be -4.2×10^{-4} radian with a standard deviation of 1.1×10^{-3} radian, while the mean of the difference in elevation was found to be -3.0×10^{-4} radian with a standard deviation of 1.0×10^{-3} radian.

(U) A fourth degree least squares ploynomial curve was fitted to both the train and elevation difference data in order to smooth the data for plotting purposes (see Figures 5 and 6).

(C) The largest error (1.7×10^{-3} radian) was in gun train and occured at a range of two-thousand yards, which gives an error of eleven feet.

IV. EFFECTS OF VELOCITY ESTIMATION ERRORS

(C) It was shown in the previous section that the estimates of target velocity are one of the major sources of error for the MK 86 system.

(U) The effect of the velocity errors in the prediction of future target position was obtained, initially, by predicting future target position from the filter's position and velocity data, and comparing the result with the actual future position. However, this comparison contains other effects, especially those due to target accelerations. Therefore, a more specific comparison was made by computing the miss-distance (in XYZ coordinates) due to the velocity errors alone.

(U) As a standard against which to measure system errors, a mean theoretical miss-distance (assuming perfect ballistics) was computed from the system's data (R22, BY22, etc.,) for maneuvering and non-maneuvering targets.

A. THEORETICAL SYSTEM MISS-DISTANCE

(C) A theoretical system projectile miss-distance was computed by comparing the predicted target position at the projectile impact time with the filtered measured target position at that time. That is, the test values of R22, BY22 and E22 (predicted projectile impact point) at time t were subtracted from the filtered values of AARNGE, ABIR and AAEO, at time $t+t_f$, where t_f is the actual time of flight, BTT2.

(U) From the differences, a corresponding miss-distance was computed from the equations:

(1) $M_R = 3$: (Range Difference)

(2) $M_B = 3 \cdot (\text{Bearing Difference in Degrees}) \cdot 1/57.29 \cdot \text{Range}$

(3) $M_E = 3 \cdot (\text{Elevation Difference in Degrees}) \cdot 1/57.29 \cdot \text{Range}$

(4) $M_T = (M_R^2 + M_B^2 + M_E^2)^{\frac{1}{2}}$,

where M_R, M_B and M_E are the miss-distances in feet due to range, bearing and elevation errors respectively; M_T is the total miss-distance in feet.

(U) A mean miss-distance for maneuvering and non-maneuvering targets was computed by

(5) $M_{T_A} = \frac{1}{n} \sum_{1}^{n} M_{T_i}$,

where n is the total number of rounds assumed to be fired at each type target (maneuvering and non-maneuvering) during all of the runs selected.

(U) In order to estimate an overall system effectiveness, one theoretical round was assumed to be fired every three seconds during runs 15 through 21 for the maneuvering target, and runs 1 through 3 and 5 through 10 for the non-maneuvering target. The miss-distance for these theoretical firings was averaged over each one-thousand yard range band out to nine-thousand yards.

(U) Tables II and III summarize the results for the maneuvering and non-maneuvering targets respectively.

B. EFFECTS OF VELOCITY ESTIMATION ERRORS ON PREDICTION

(C) The effect of errors in the filter's estimates of velocity in predicting future target position in each of the X-, Y- and Z-directions was determined initially by comparing the filtered target position estimates of ZSUBN (Z), ZSUBN+1 (X) and ZSBUN+2 (Y) at time $t+t_f$

with the position predicted from the filtered position and velocity data at time t, where t_f here is the <u>mean</u> time of flight for each run. That is, to find the predicted position, the current filtered velocities in the X-, Y- and Z-directions were multiplied by the run mean time of flight and added to the current filtered position.

(U) These comparisons were made for a maneuvering BQM target (medium-speed), and a non-maneuvering high bearing rate TDU target (slow speed). Runs 11 and 12 were selected for the TDU and runs 15 and 17 were selected for the BQM.

(U) Figures 7 through 9 show the comparison between the actual (i.e. filtered) and the predicted target locations in the X-, Y- and Z-directions, respectively, for the TDU and figures 10 through 12 show the same comparisons for the BQM. The absolute values of the differences between the predicted and smoothed X, Y and Z positions for the same runs are plotted against target range in Figures 13 through 18.

(C) Figures 8 and 10 suggest that, with no target maneuvers, the system's velocity estimates produce quite accurate future target position estimates. The other figures for the TDU show that, with small, slow-speed maneuvers, the system's estimates of target velocity are accurate enough to achieve a hit (miss-distance less than fifty feet) over sixty percent of the time.

(C) Figures 11 and 12 show that the system does not produce accurate velocity estimates for a medium-speed maneuvering target (maneuver acceleration of 0.3 g in the Y-direction and 0.17 g in the Z-direction.

C. MISS-DISTANCE INDUCED BY VELOCITY ESTIMATION ERRORS

(U) A more detailed analysis of the effects of errors in the velocity

estimates was obtained by computing the miss-distance specifically due to the velocity errors of theoretical rounds assumed to be fired at three-second intervals. The differences between the actual and estimated valocities when computed as in section III B yield the miss-distances as follows:

$$(6)\quad \dot{M}_X = (\dot{X}\text{ Difference})\cdot 3\cdot t_f$$

$$(7)\quad \dot{M}_Y = (\dot{Y}\text{ Difference})\cdot 3\cdot t_f$$

$$(8)\quad \dot{M}_Z = (\dot{Z}\text{ Difference})\cdot 3\cdot t_f$$

$$(9)\quad M_D = (\dot{M}_X^2 + \dot{M}_Y^2 + \dot{M}_Z^2)^{\frac{1}{2}} ,$$

where $\dot{M}_X$, $\dot{M}_Y$ and $\dot{M}_Z$ are the miss-distances in feet due to the velocity errors in the X-, Y- and Z-directions, M_D is the total miss-distance in feet, and t_f is the actual time of flight, BTT2.

(U) A mean miss-distance (M_{D_A}) was calculated for maneuvering and non-maneuvering targets using

$$(10)\quad M_{D_A} = \frac{1}{n}\sum_{1}^{n} M_{D_i} ,$$

where n is the number of data points.

(U) The results of these calculations are summarized in Tables II and III for comparison with the theoretical system miss-distance.

(C) For both type targets, maneuvering and non-maneuvering, the magnitude of M_{D_A} corresponds to about seventy precent of the magnitude of M_{T_A}. Thus it appears that the velocity estimation errors could account for a large part of the system miss-distance.

V. THEORETICAL SYSTEM EFFECTIVENESS

(U) In order to determine the effectiveness of the system against maneuvering and non-maneuvering targets, a single-shot hit probability, a round placement effectiveness measure and a system engagement effectiveness measure were computed using the system's theoretical miss-distance.

A. SINGLE-SHOT HIT PROBABILITY

(U) Using the miss-distances computed for the theoretical firings in section IV A, a single-shot hit probability for each five-hundred yard range band was computed for both maneuvering and non-maneuvering targets by dividing the number of times the miss-distance was less than fifty feet by the number of miss-distance calculations for that range band.

(U) These probabilities were averaged for each range band over all the runs for each type target (maneuvering and non-maneuvering) with the results shown in Table 4.

B. EFFECTIVENESS MEASURES

(U) A theoretical round placement effectiveness measure and a system engagement effectiveness measure were computed for maneuvering and non-maneuvering targets.

1. Round Placement Effectiveness

(C) The round placement effectiveness measure, P_{Si}, was computed for each theoretical round fired during a run by weighting the projectile miss-distance by

(11) $P_{Si} = EXP\left(\frac{-M_i^2}{36}\right)$,

from ref. 2, where M_i is the theoretical miss-distance M_{Ti} determined in section IV A. Ten theoretical rounds, spaced at three second intervals, were assumed to be fired at the target. To obtain more data points, two such "firing runs" were performed on each set of target data. A mean value of P_{Si} for each one-thousand yard range band out to nine-thousand yards was computed by averaging the results over all the runs.

(U) Table V gives the results for the average P_{Si} for each range band for maneuvering and non-maneuvering targets.

2. System Engagement Effectiveness

(C) The system engagement effectiveness measure, P_S , was determined for each run selected by

(12) $P_S = 1 - \prod_{1}^{J} (1 - P_{Si})$,

from Ref. 2, where J is the number of rounds fired, and P_{Si} is the round placement effectiveness measure computed above.

(U) Table VI shows the results for runs 15 through 20 for the maneuvering target and runs 5 through 7 and 11, 12 and 14 for the non-maneuvering target.

(C) The system effectiveness measure can be loosely interpreted as a measure of engagement kill probability if other factors, such as fuze reliability, system availability, etc., are not considered.

(C) It was found that as the number of theoretical rounds fired

was increased to fifteen rounds per run, the average system effectiveness measure for the maneuvering target increased from 0.808 to 0.932. This shows that, as expected, an increased firing rate, especially at the shorter ranges, causes an appreciable improvement in system effectiveness.

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VI. CONCLUSIONS

(C) A major part of the overall system error is caused by errors in the 3-D filter's estimates of target velocity. From this, there appears to be little chance of significant improvement in the system's performance (especially against maneuvering targets) unless better velocity estimates can be obtained.

(C) Since the velocity estimation process necessarily introduces a time lag, one should ask whether it is possible to establish a baseline -- the "best" that can be achieved. The first problem that should be addressed is a study of the filter from this point of view. After the baseline has been established, the limits on the system's performance could be determined and an attempt made to improve the filter's performance toward this ultimate standard.

(C) Unless significant improvements are made in the velocity estimates, no attempt at "curvilinear prediction" should be made, since the time lag in the acceleration estimates will be even greater, and the acceleration term in the prediction process could further degrade the system's performance against maneuvering targets.

TABLE I.

RUN NR.	TEST	EVENT	TARGET	TARGET RUN	MANEUVERING
1	8	1	A4	1	
2	8	1	A4	2	
3	8	1	A4	3	
4	8	1	A4	4	X
5	9A	1	A4	11	
6	9A	3	A4	1	
7	9C	1	A4	1	
8	16	1	SLEEVE	F1A	
9	16	1	SLEEVE	F1B	
10	16	1	SLEEVE	F2B	
11	17	2	TDU	15	
12	17	2	TDU	16	
13	17	2	TDU	16A	
14	17	2	TDU	17	
15	18	3	BQM	F1	X
16	18	3	BQM	F2	X
17	18	3	BQM	F3	X
18	18	3	BQM	1	X
19	18	3	BQM	2	X
20	18	3	BQM	3	X
21	18	3	BQM	4	X

[redacted]

TABLE II.

RANGE BAND(YARDS)	THEORETICAL MISS-DISTANCE(FEET)	VELOCITY ERROR MISS-DISTANCE(FEET)
0-1000	31	25
1001-2000	43	34
2001-3000	74	53
3001-4000	118	85
4001-5000	162	121
5001-6000	228	157
6001-7000	293	222
7001-8000	374	258
8001-9000	511	363

Average Theoretical and Velocity Error Induced Miss-Distances in Feet for Maneuvering Targets

[redacted]

[redacted]

TABLE III.

RANGE BAND(YARDS)	THEORETICAL MISS-DISTANCE(FEET)	VELOCITY ERROR MISS-DISTANCE(FEET)
0-1000	10	3
1001-2000	14	9
2001-3000	22	17
3001-4000	37	28
4001-5000	53	37
5001-6000	74	54
6001-7000	91	67
7001-8000	136	98
8001-9000	188	130

Average Theoretical and Velocity Error Induced Miss-Distances for Non-Maneuvering Targets

[redacted]

TABLE IV.

RANGE BAND (YARDS)	MANEUVERING	NON-MANEUVERING
0-500	0.41	0.78
501-1000	0.38	0.75
1001-1500	0.33	0.71
1501-2000	0.27	0.67
2001-2500	0.18	0.64
2501-3000	0.12	0.58
3001-3500	0.07	0.53
3501-4000	0.02	0.47
4001-4500	0.0	0.40
4501-5000	0.0	0.33
5001-5500	0.0	0.21
5501-6000	0.0	0.07
6001-6500	0.0	0.02
6501-7000	0.0	0.0
7001-7500	0.0	0.0
7501-8000	0.0	0.0
8001-8500	0.0	0.0
8501-9000	0.0	0.0

Average Single-Shot Hit Probabilities for Maneuvering and Non-Maneuvering targets.

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TABLE V.

ROUND PLACEMENT EFFECTIVENESS

RANGE BAND (YARDS)	MANEUVERING TGT. AVERAGE P_{Si}	NON-MANEUVERING TGT. AVERAGE P_{Si}
0-1000	0.42	0.76
1001-2000	0.30	0.68
2001-3000	0.13	0.54
3001-4000	0.03	0.36
4001-5000	0.01	0.23
5001-6000	0.0	0.13
6001-7000	0.0	0.08
7001-8000	0.0	0.02
8001-9000	0.0	0.0

TABLE VI

SYSTEM ENGAGEMENT EFFECTIVENESS

RUN NR.	MANEUVERING	SYSTEM EFFECTIVENESS
5		1.0
6		0.99
7		0.99
11		0.98
12		0.99
14		1.0
15	X	0.81
16	X	0.81
17	X	0.76
18	X	0.77
19	X	0.85
20	X	0.85

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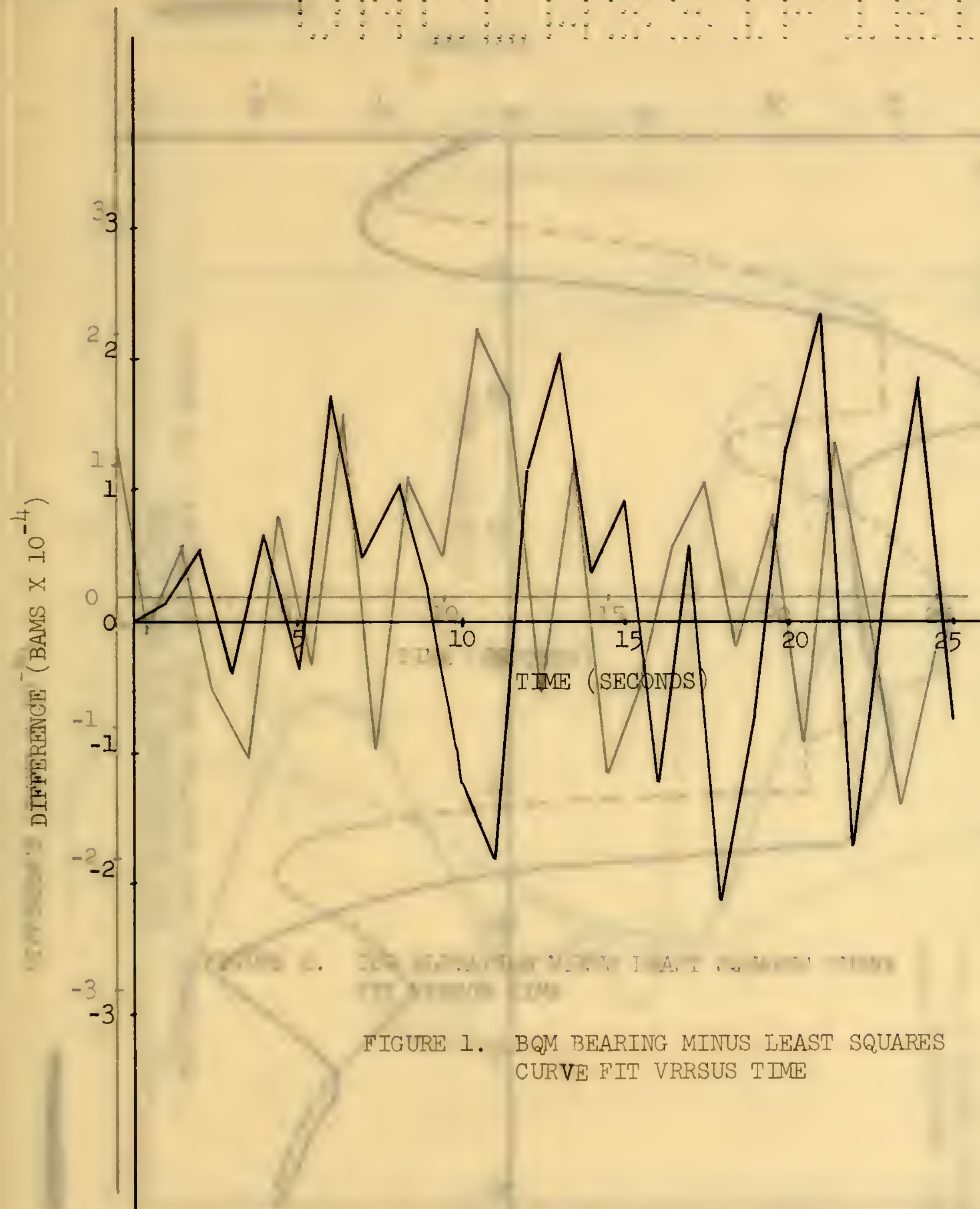

FIGURE 1. BQM BEARING MINUS LEAST SQUARES CURVE FIT VRRSUS TIME

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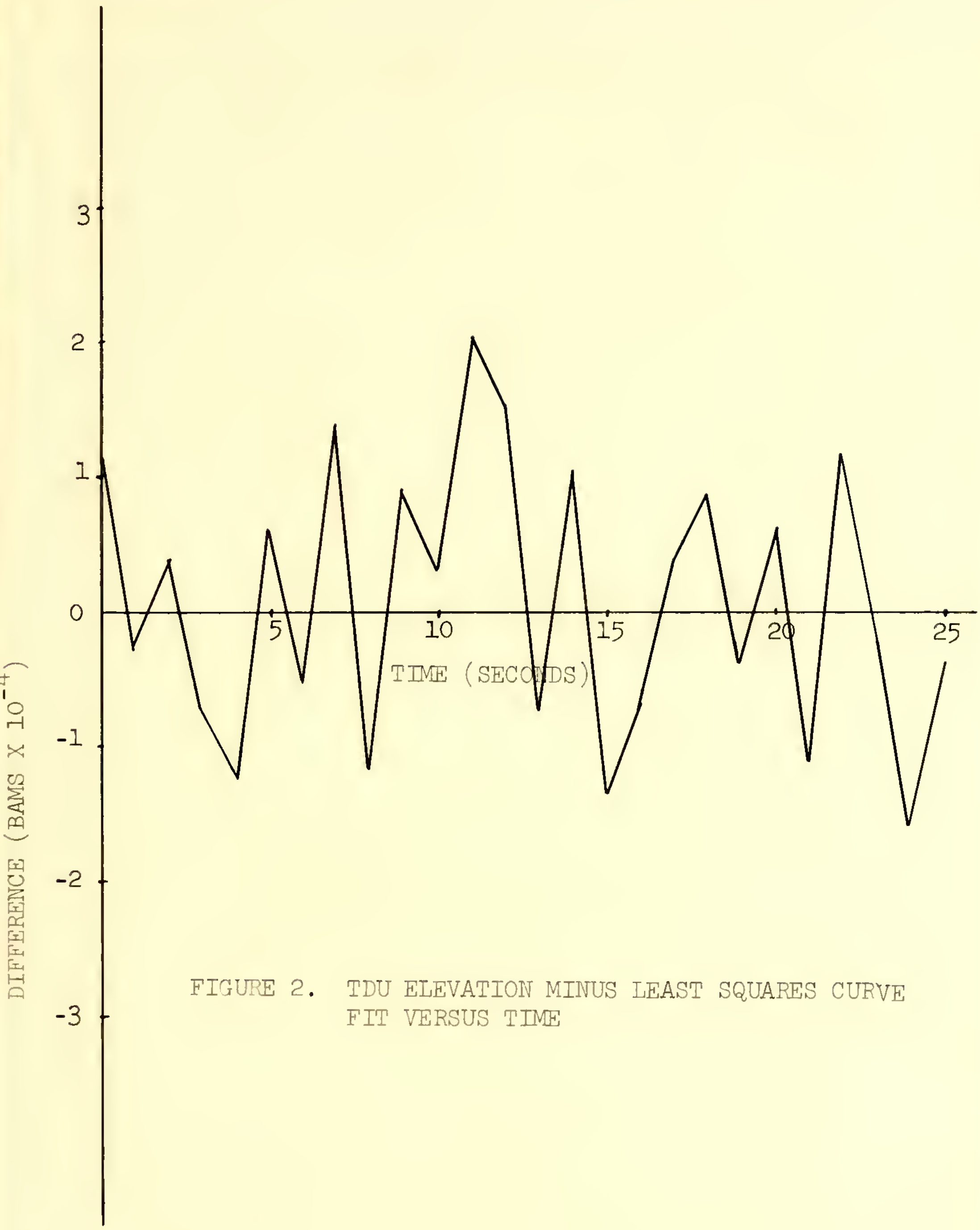
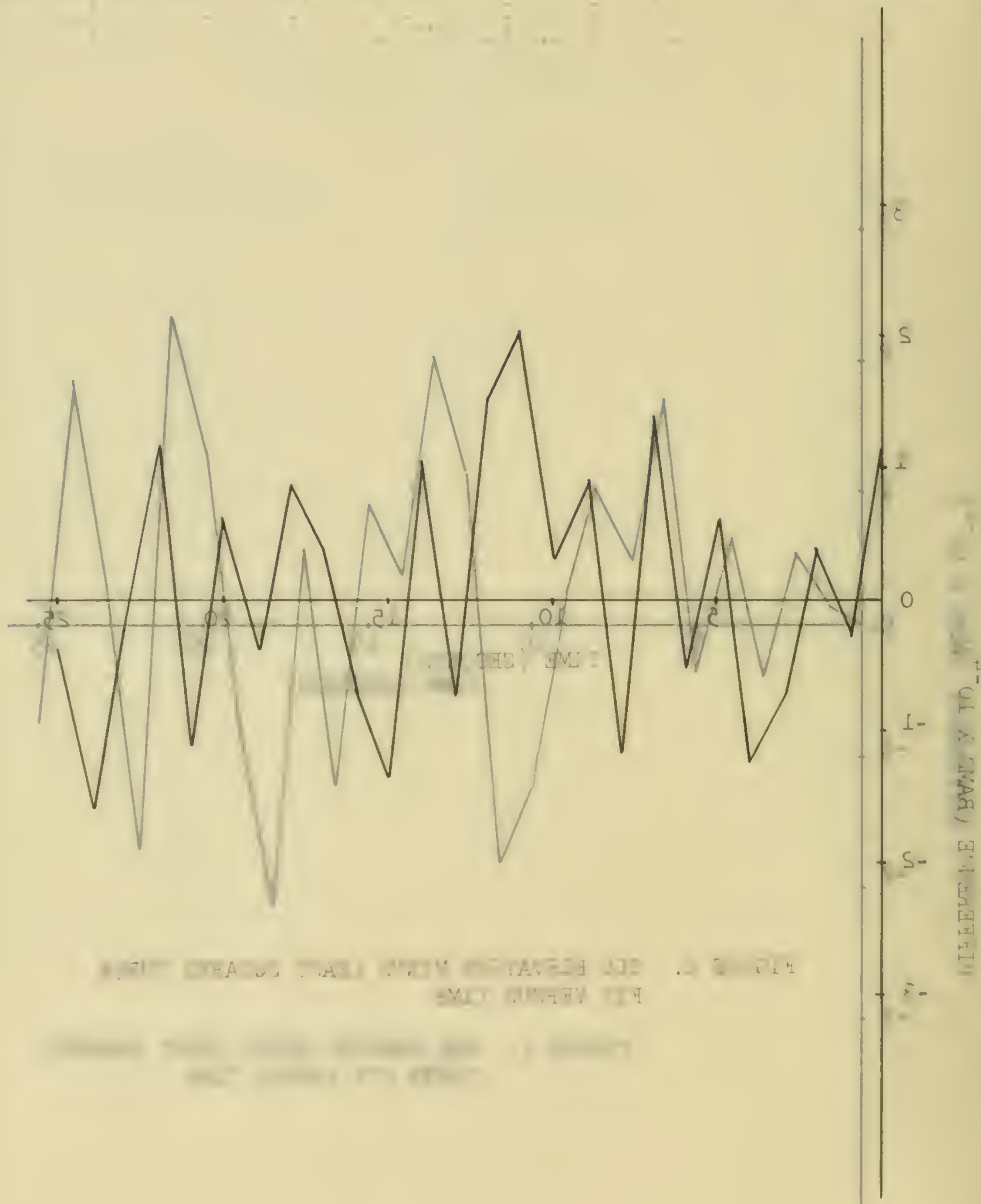


FIGURE 2. TDU ELEVATION MINUS LEAST SQUARES CURVE FIT VERSUS TIME



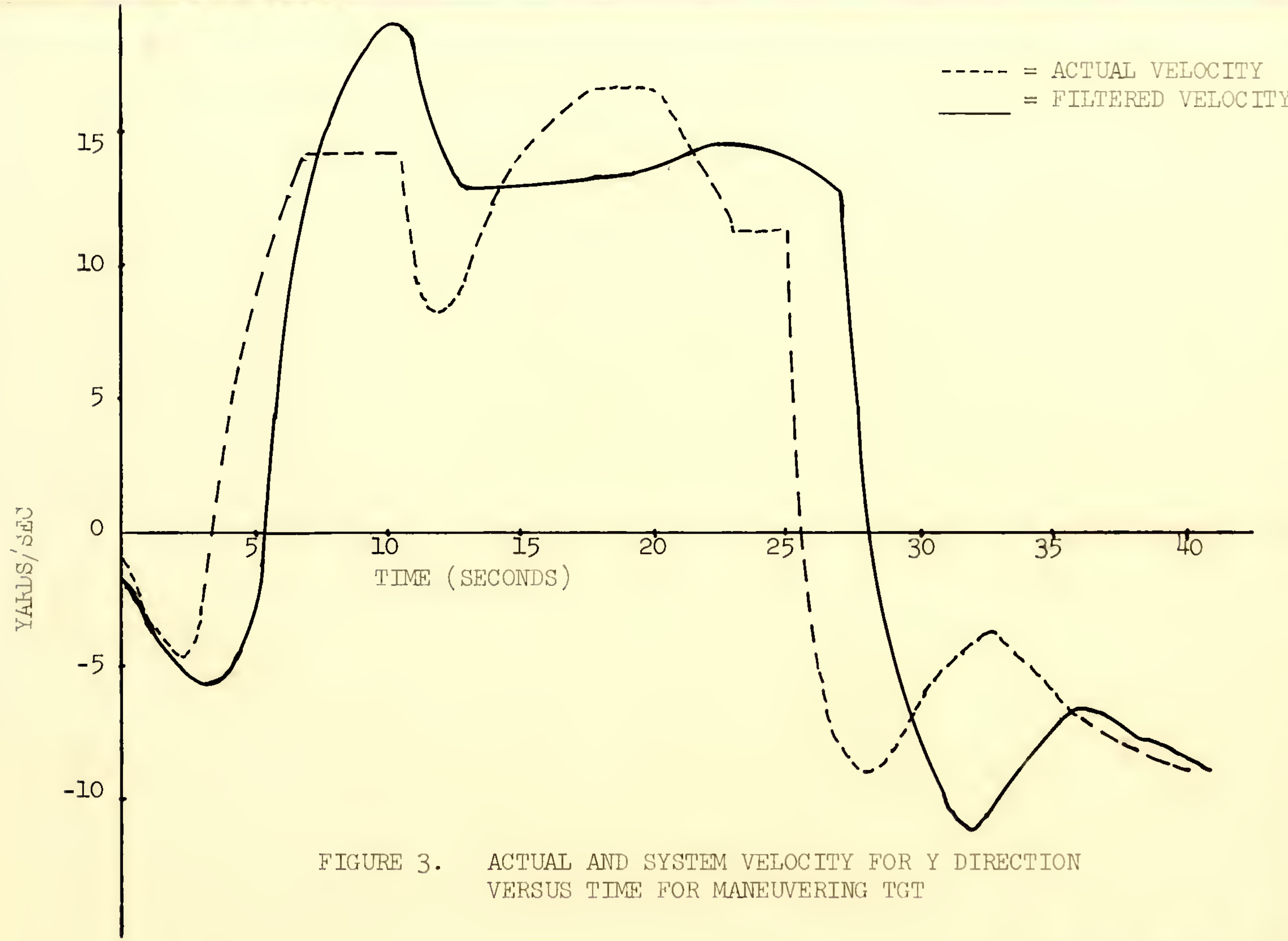
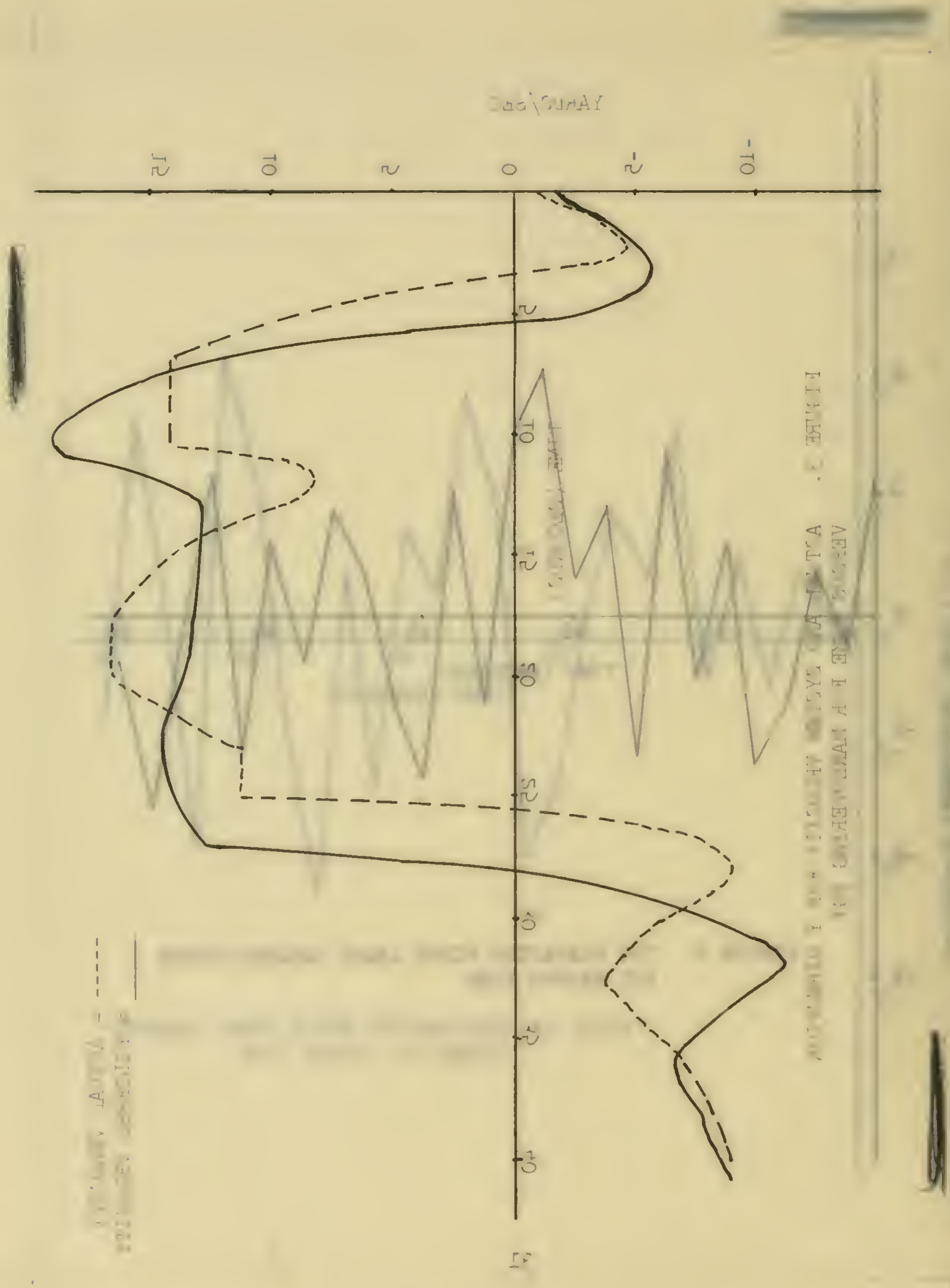


FIGURE 3. ACTUAL AND SYSTEM VELOCITY FOR Y DIRECTION VERSUS TIME FOR MANEUVERING TGT



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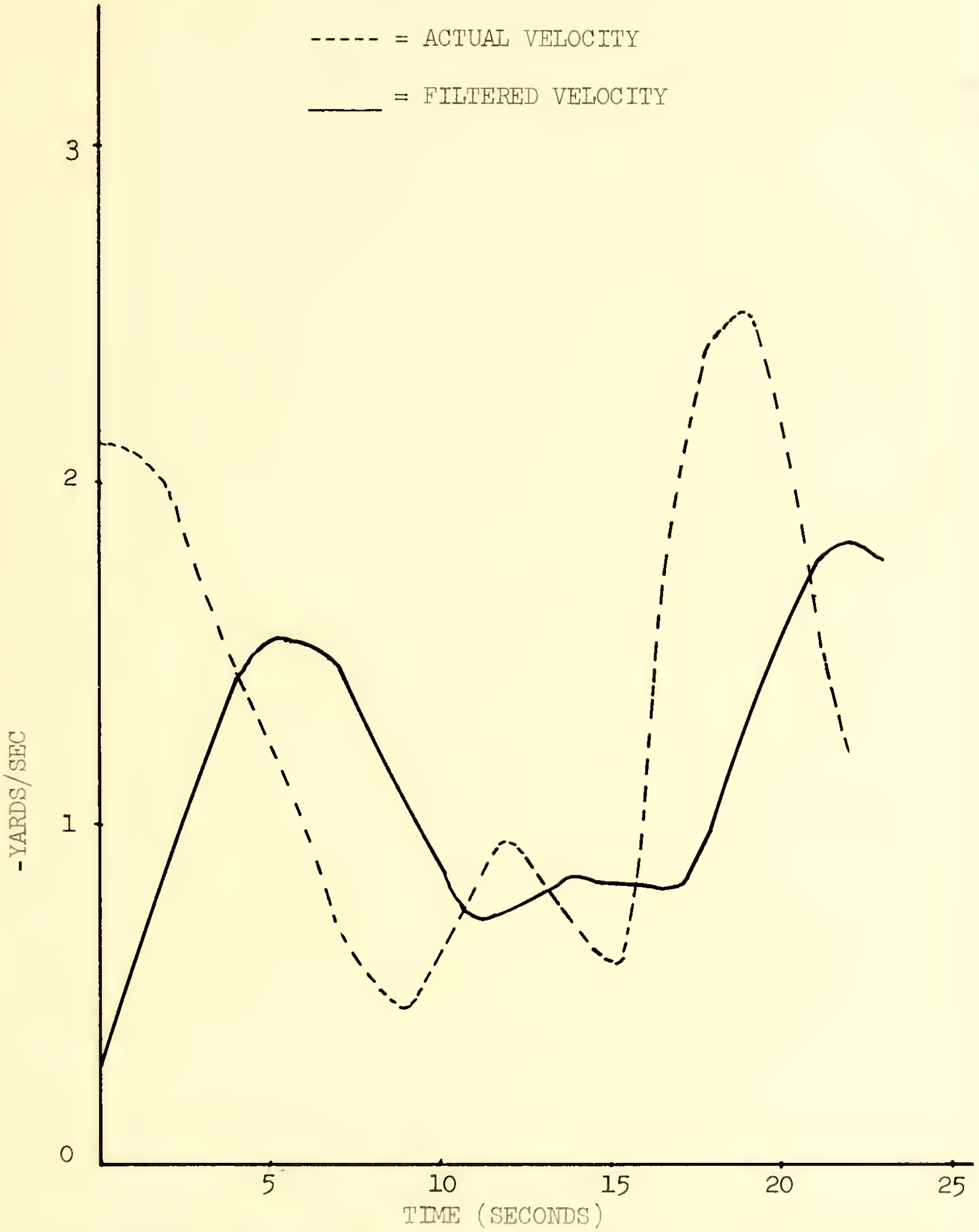

FIGURE 4. ACTUAL AND SYSTEM VELOCITY FOR Z DIRECTION VERSUS TIME FOR NON-MANEUVERING TGT

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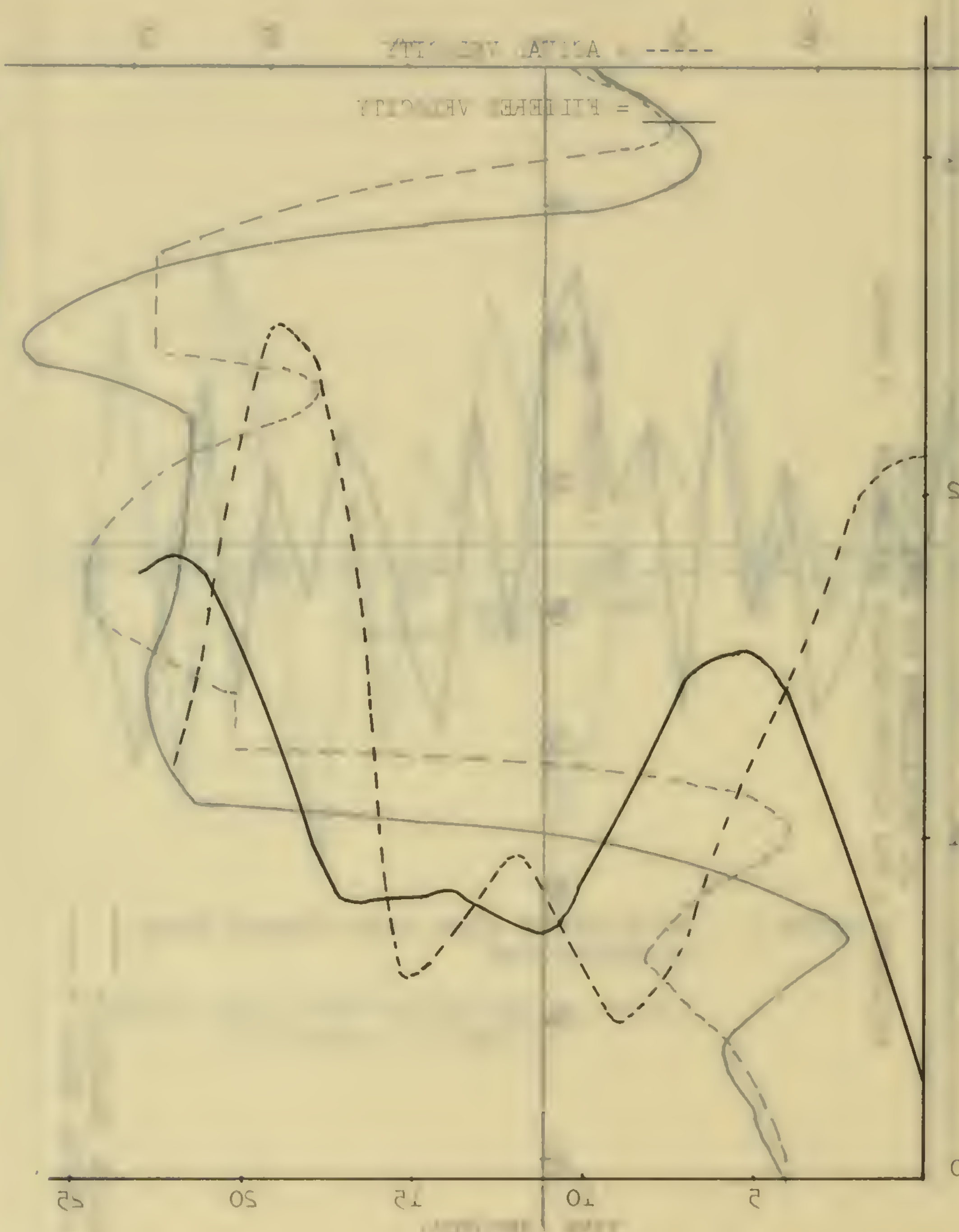

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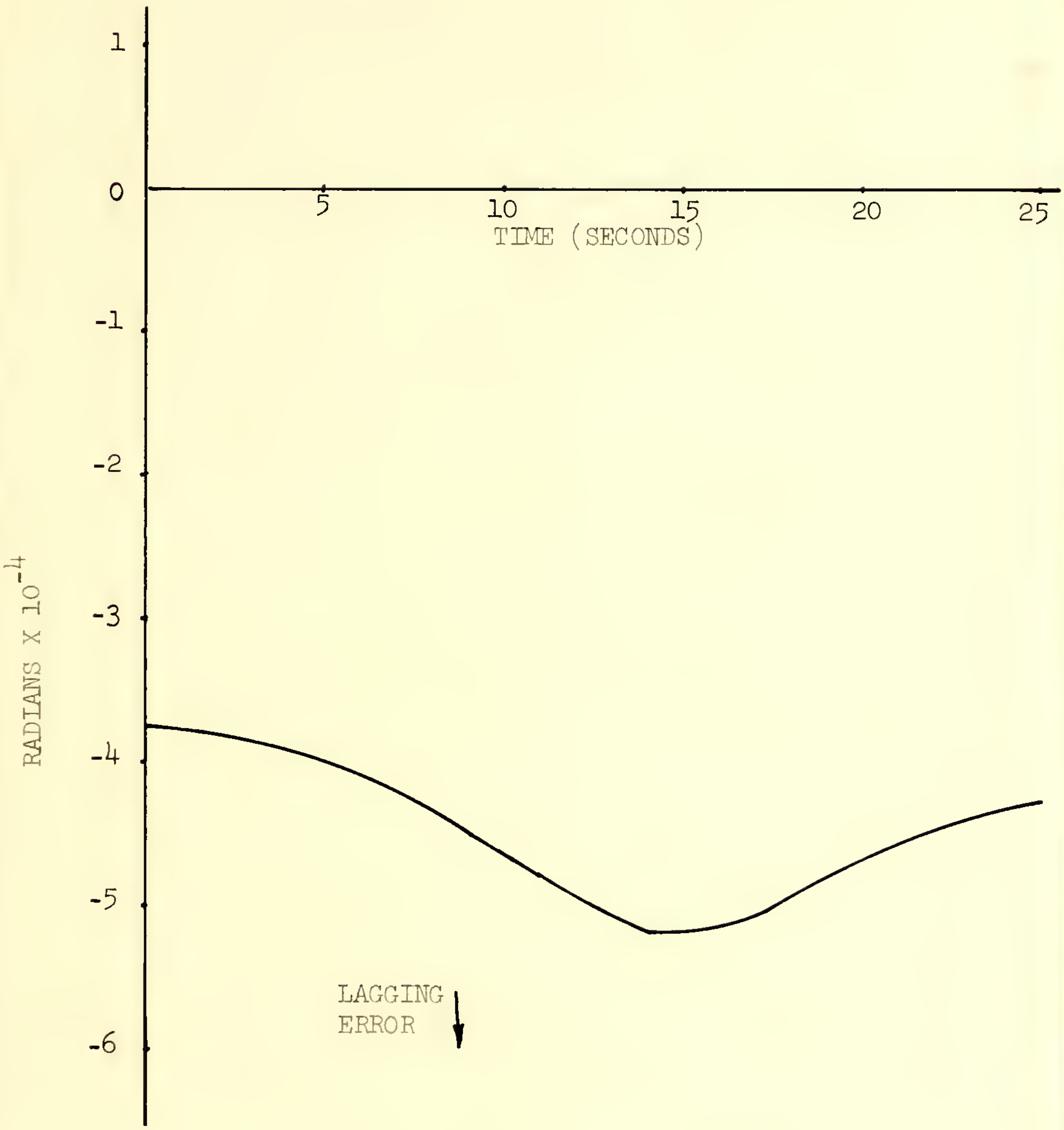
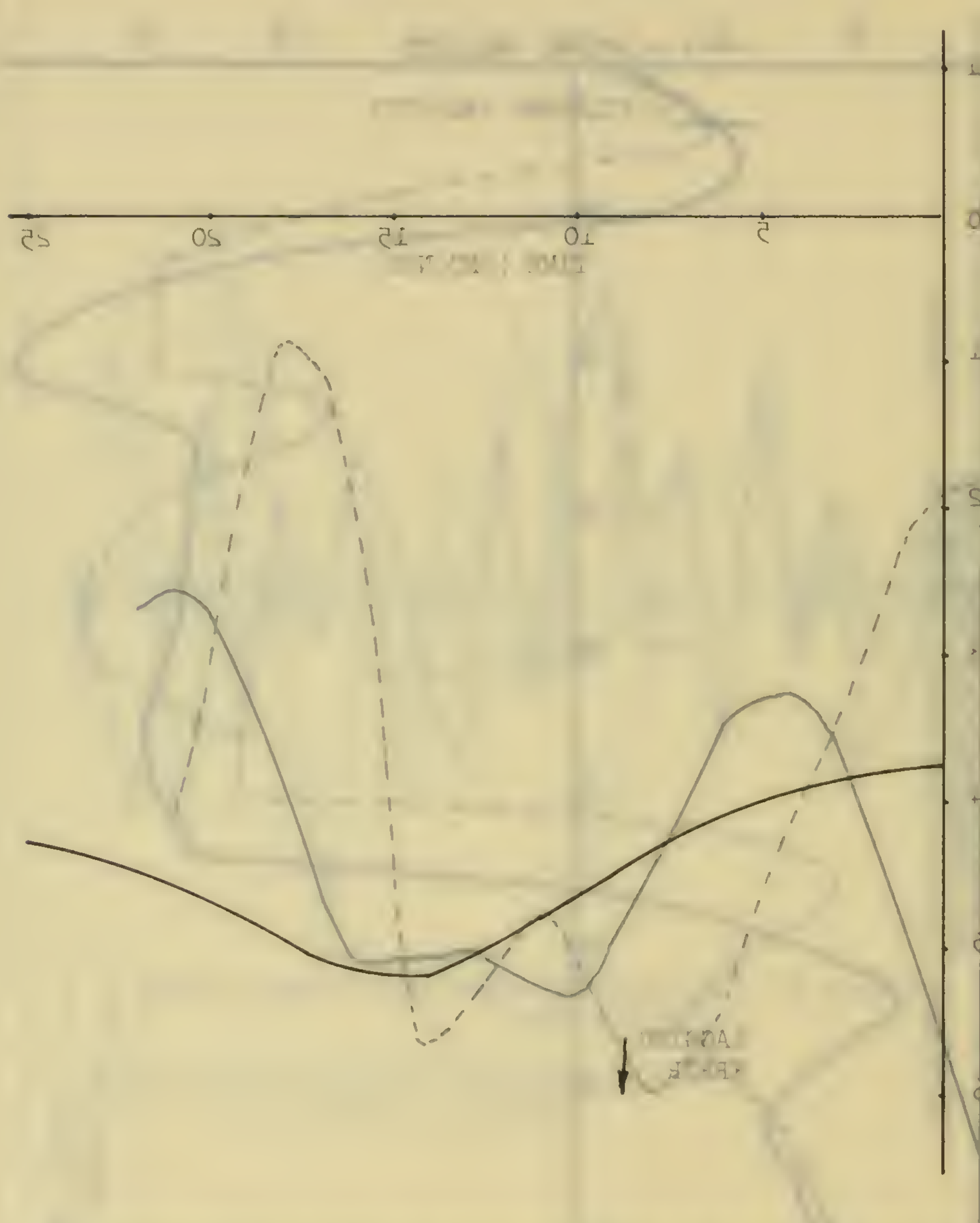


FIGURE 5. GUN FOLLOWING ERROR IN TRAIN VERSUS TIME



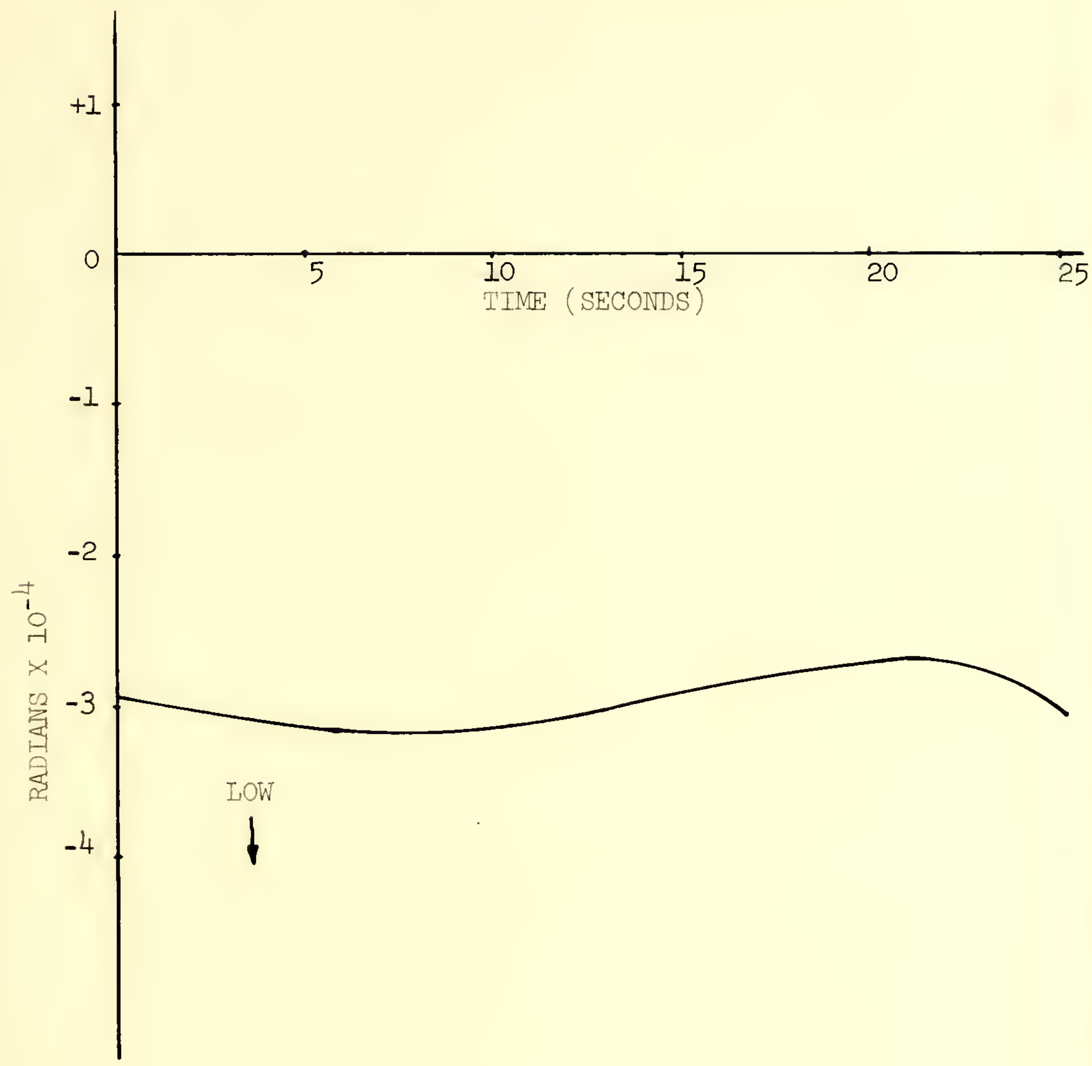


FIGURE 6. GUN FOLLOWING ERROR IN ELEVATION VERSUS TIME

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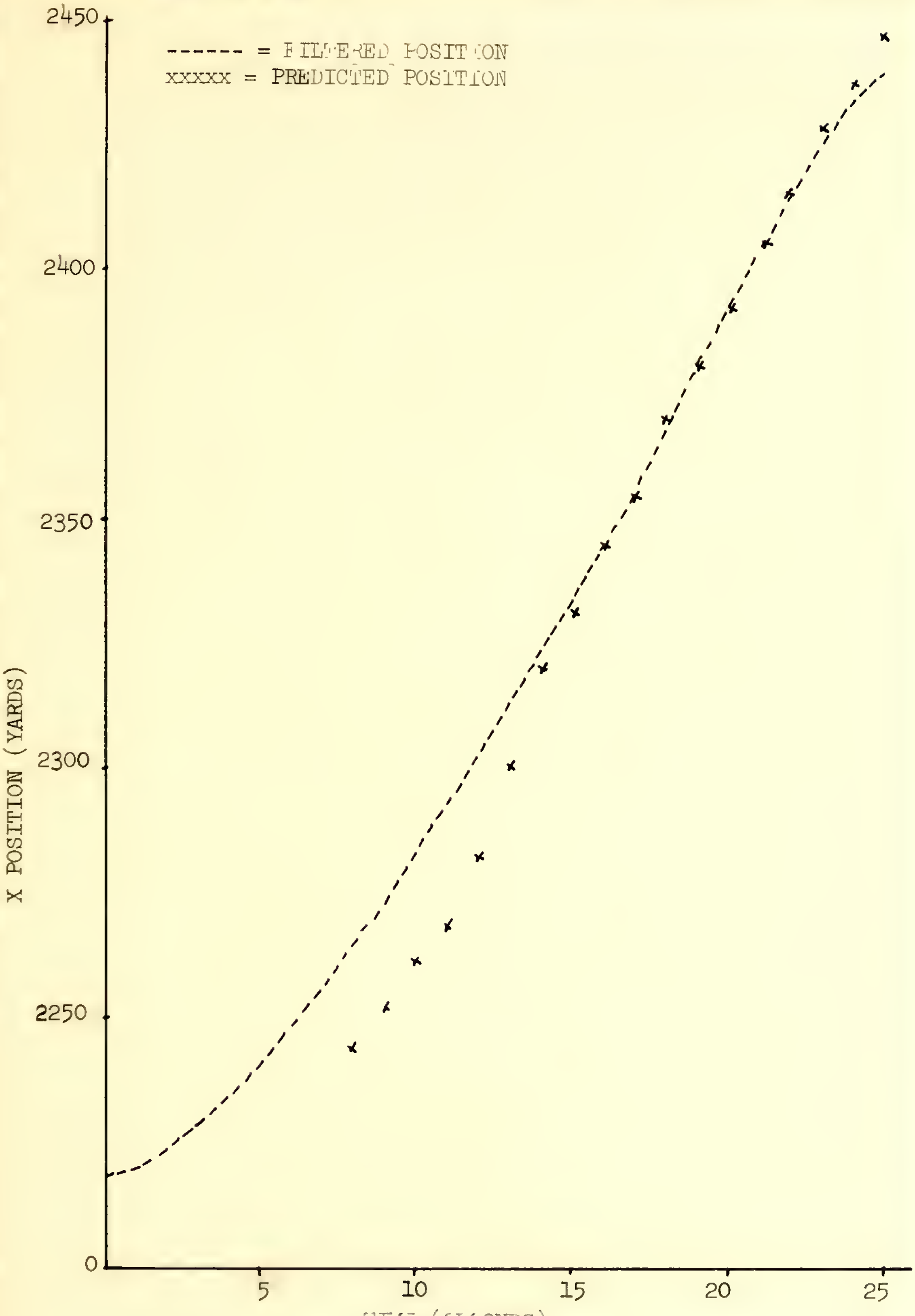


FIGURE 7. X DIRECTION WITH 6 SECONDS PREDICTION FOR NON-MANEUVERING TGT

[redacted]


X POSITION (YARDS)
2450
2400
2350
2300
2250
0
5
10
15
20
25

[redacted]

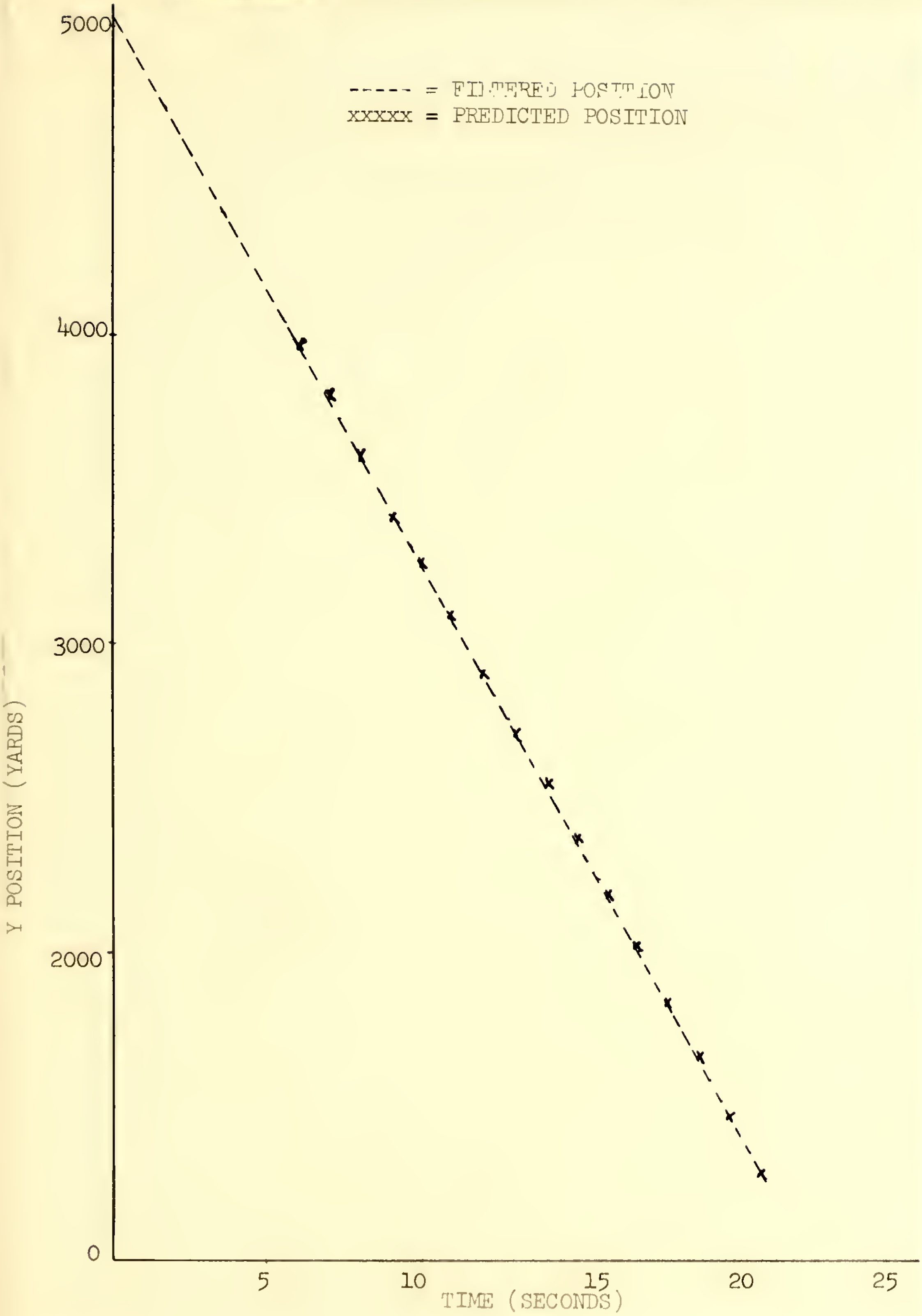
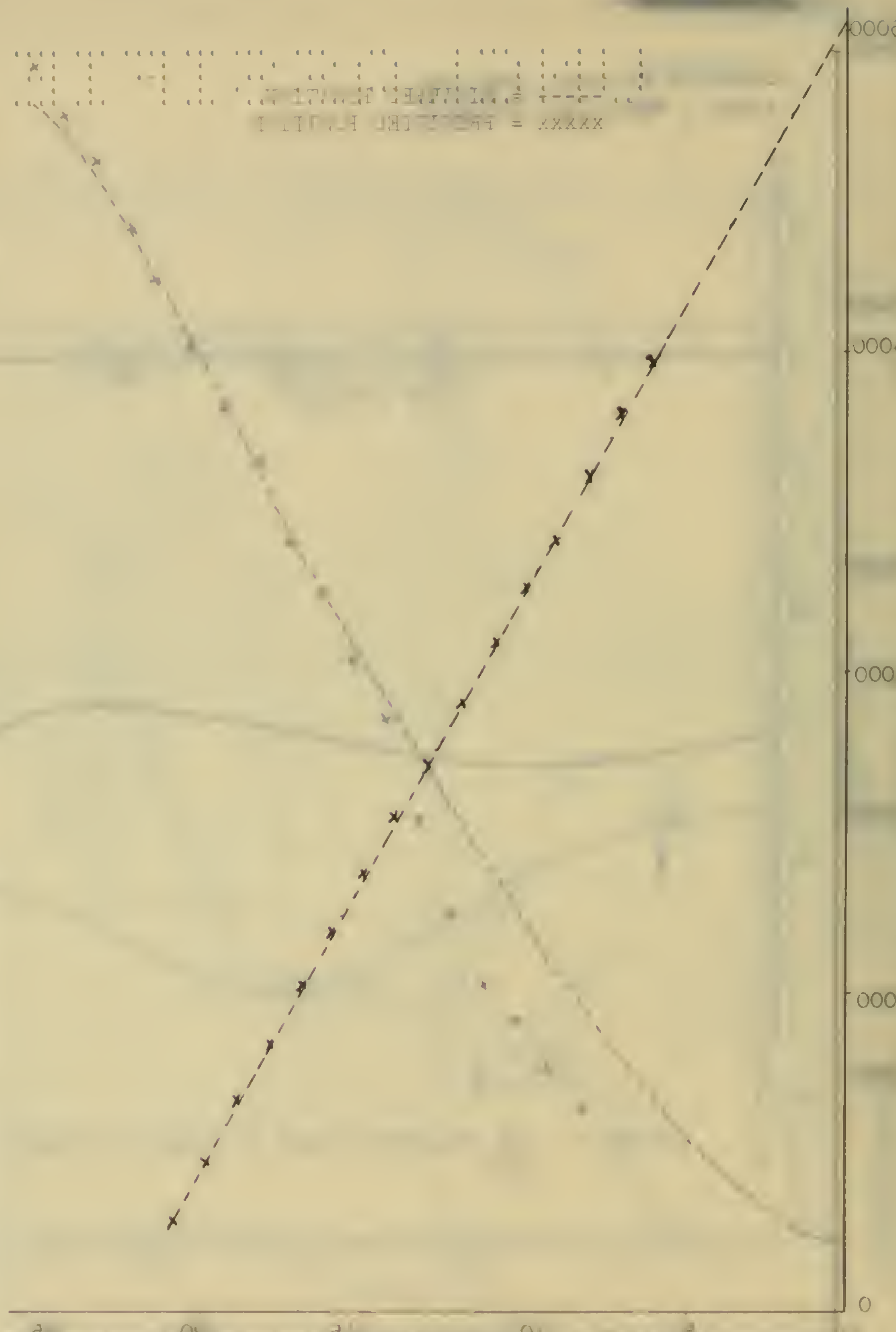


FIGURE 8. Y DIRECTION WITH 6 SECONDS PREDICTION FOR NON-MANEUVERING TGT

[redacted]



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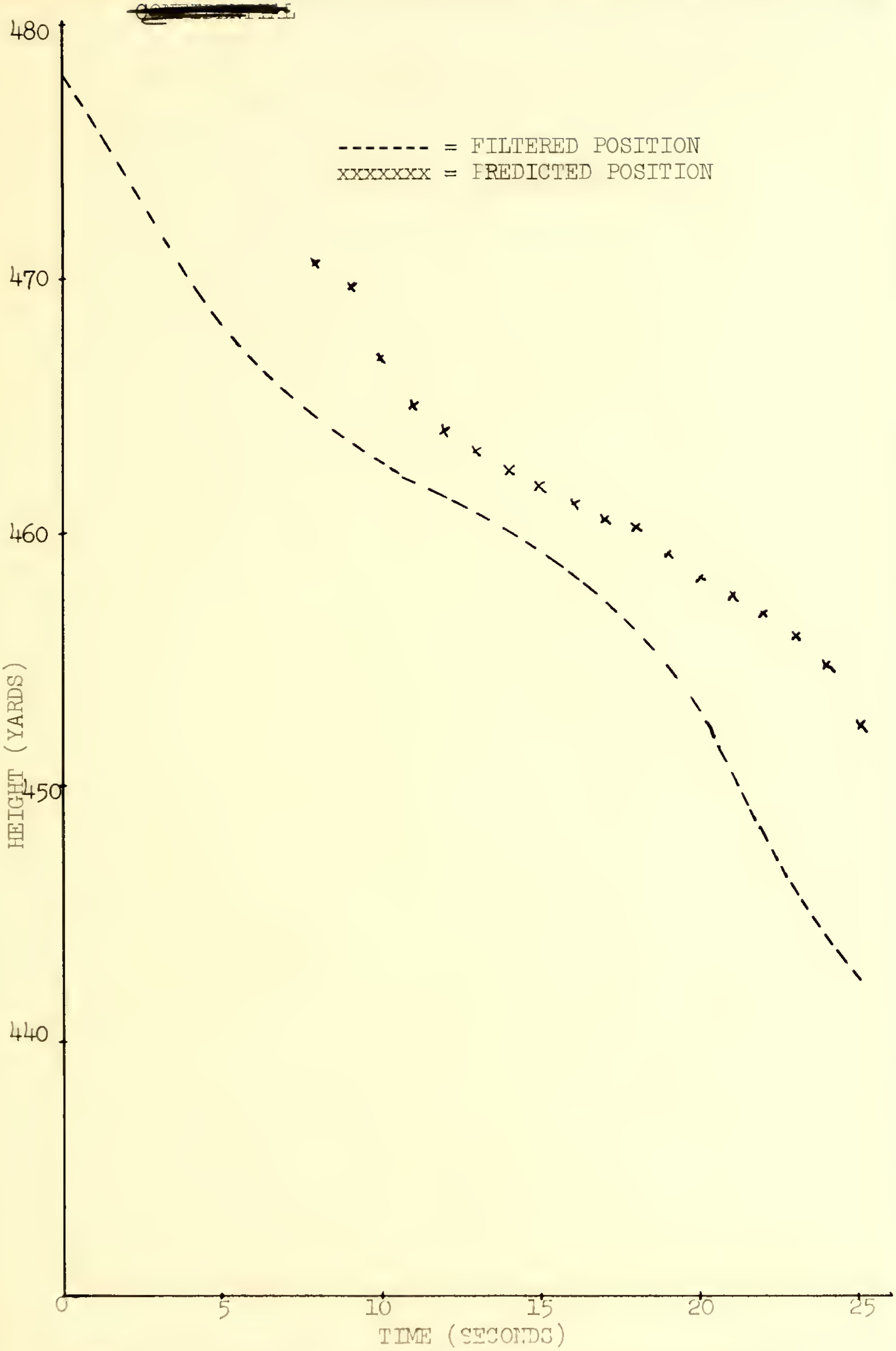

FIGURE 9. Z DIRECTION WITH 6 SECONDS PREDICTION FOR NON-MANEUVERING TGT

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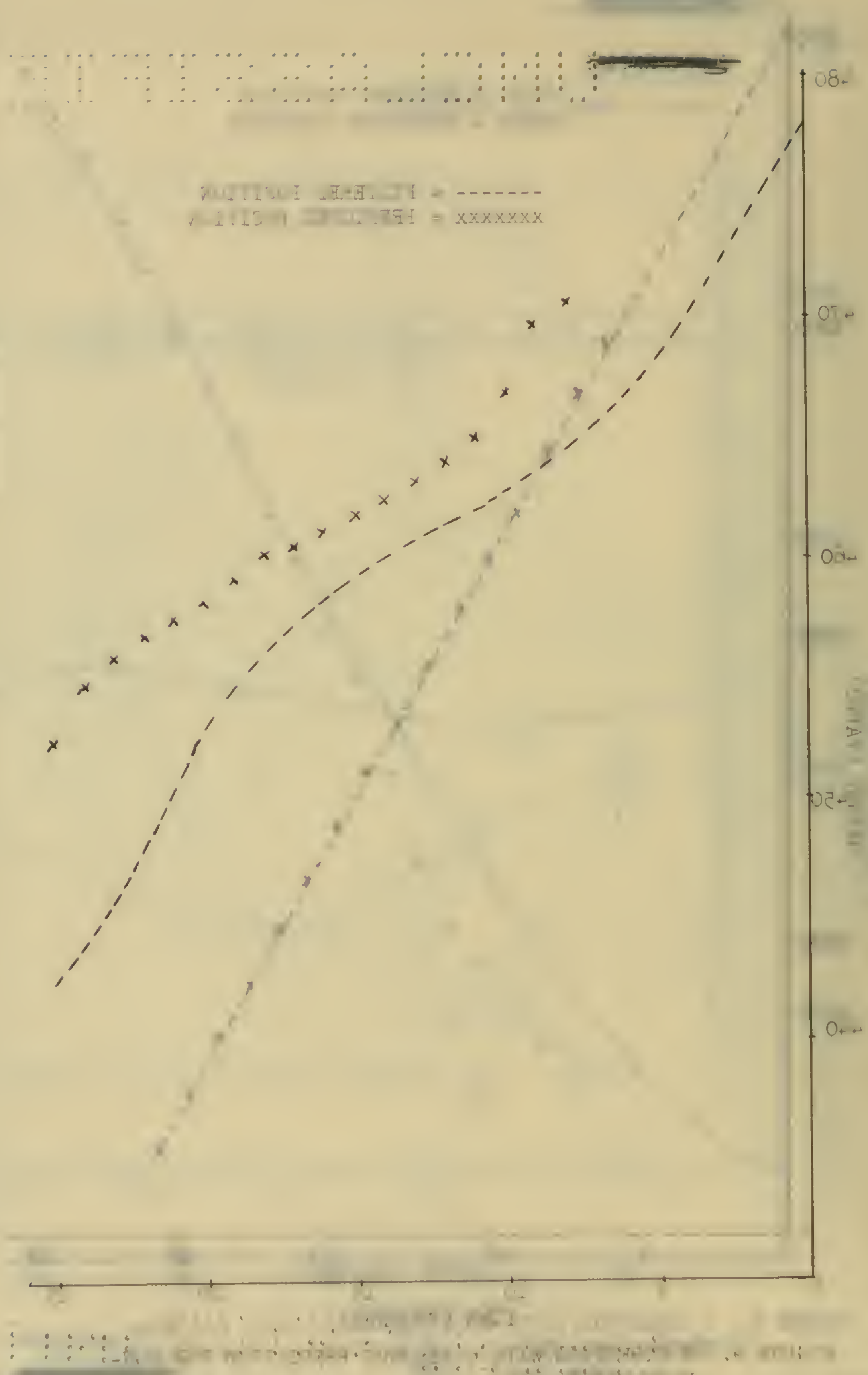

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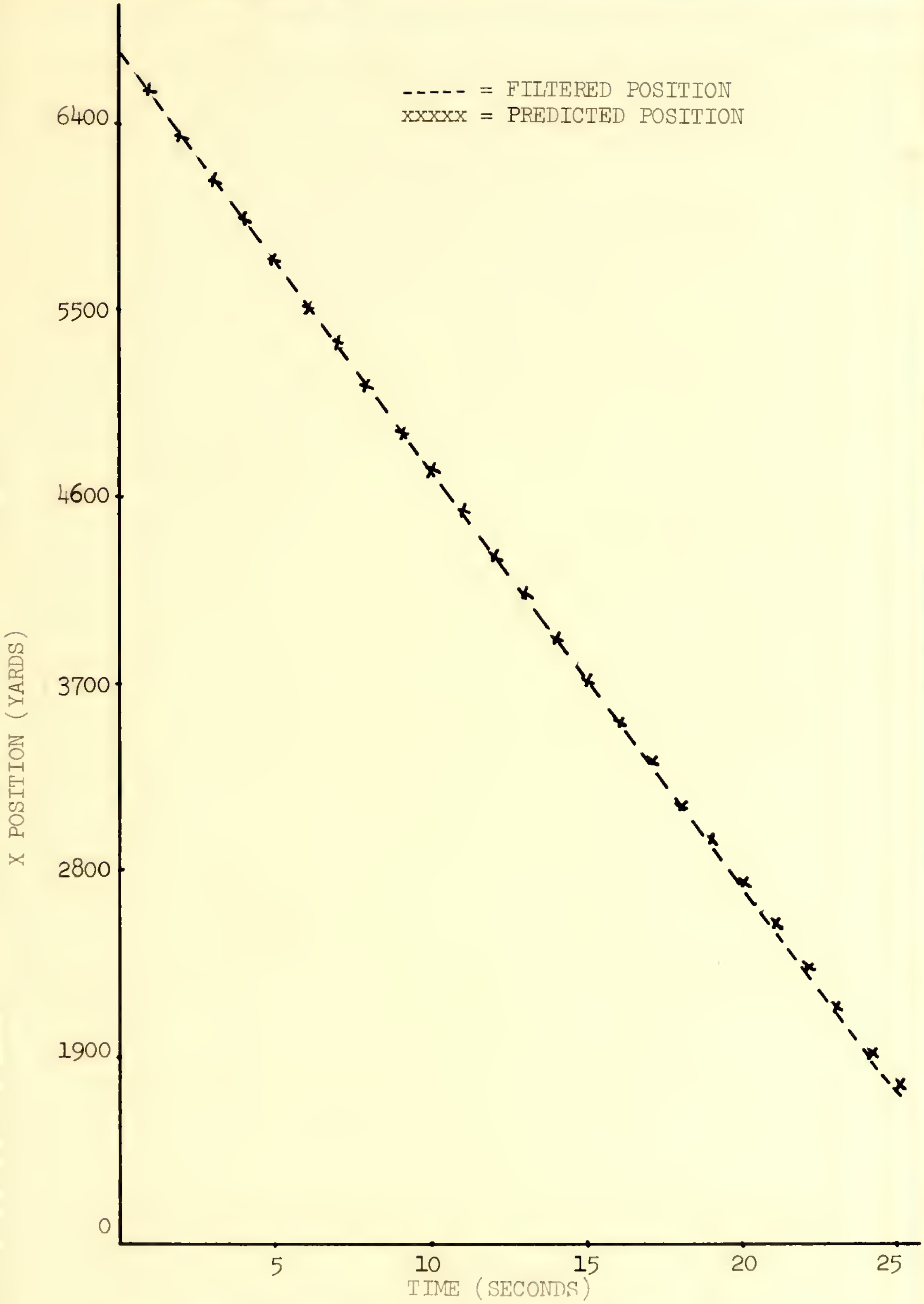

FIGURE 1C. X DIRECTION WITH 8 SECONDS PREDICTION FOR MANEUVERING TGT VERSUS TIME

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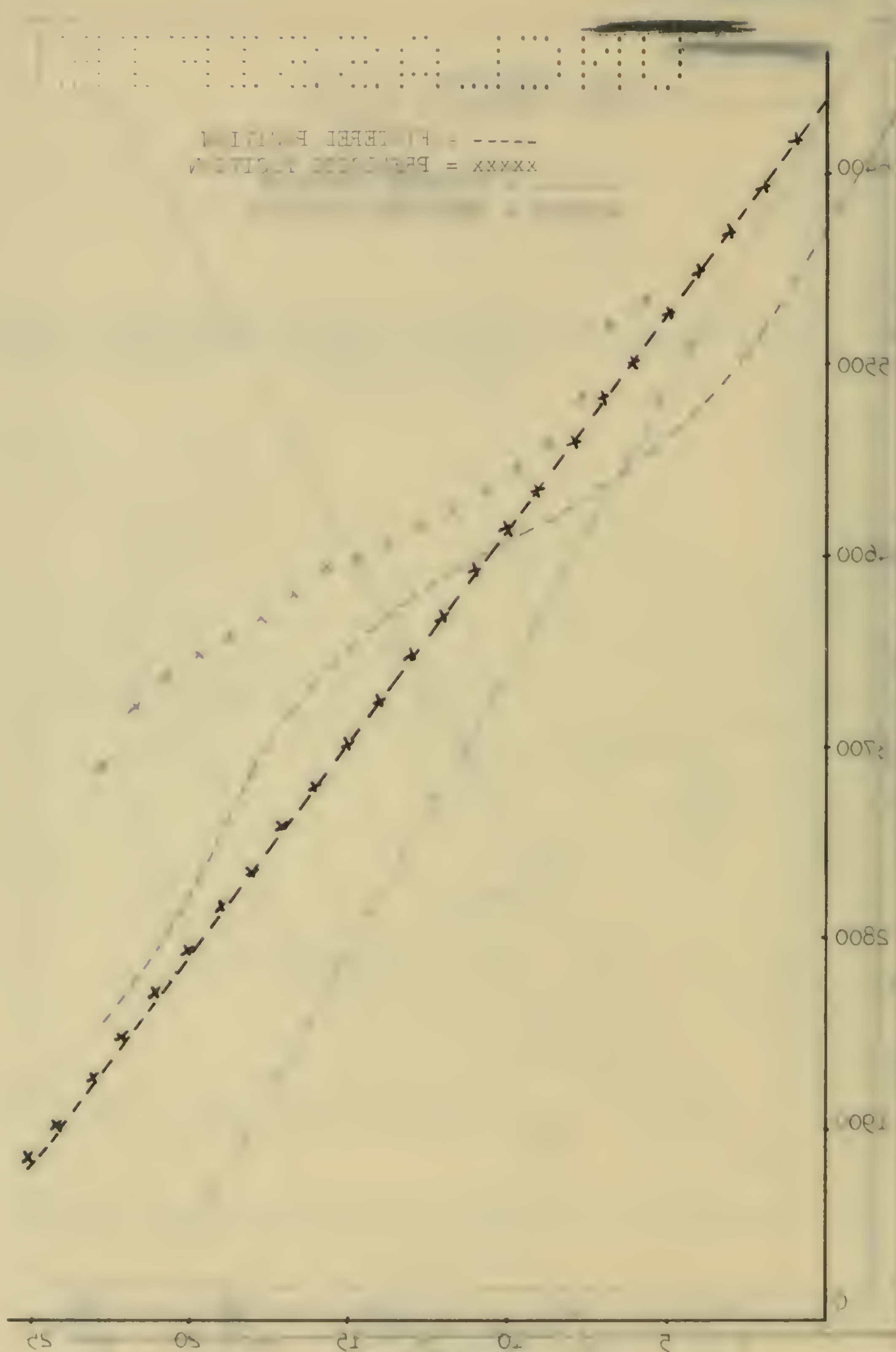

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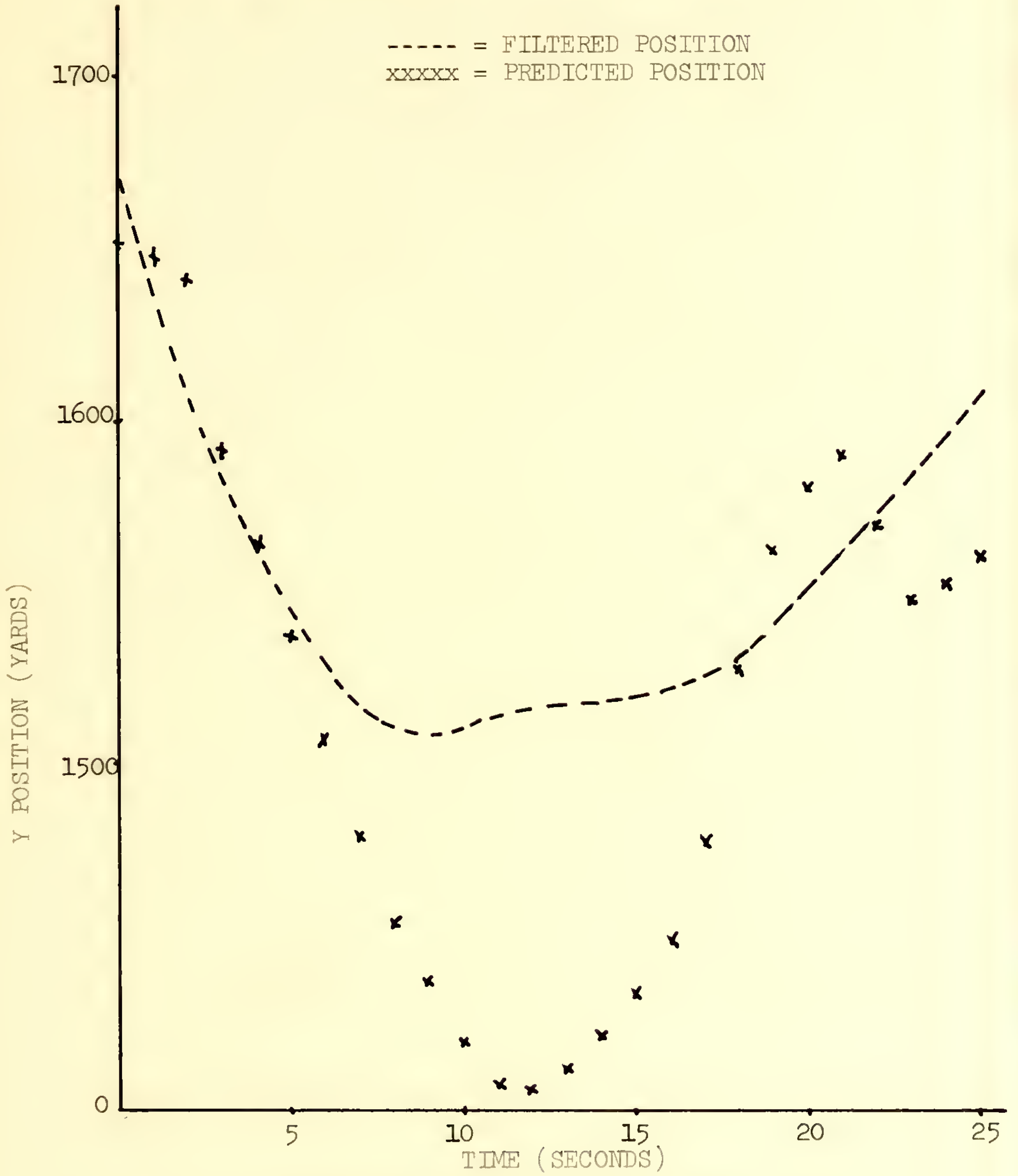

FIGURE 11. Y DIRECTION WITH 8 SECONDS PREDICTION FOR MANEUVERING TGT VERSUS TIME

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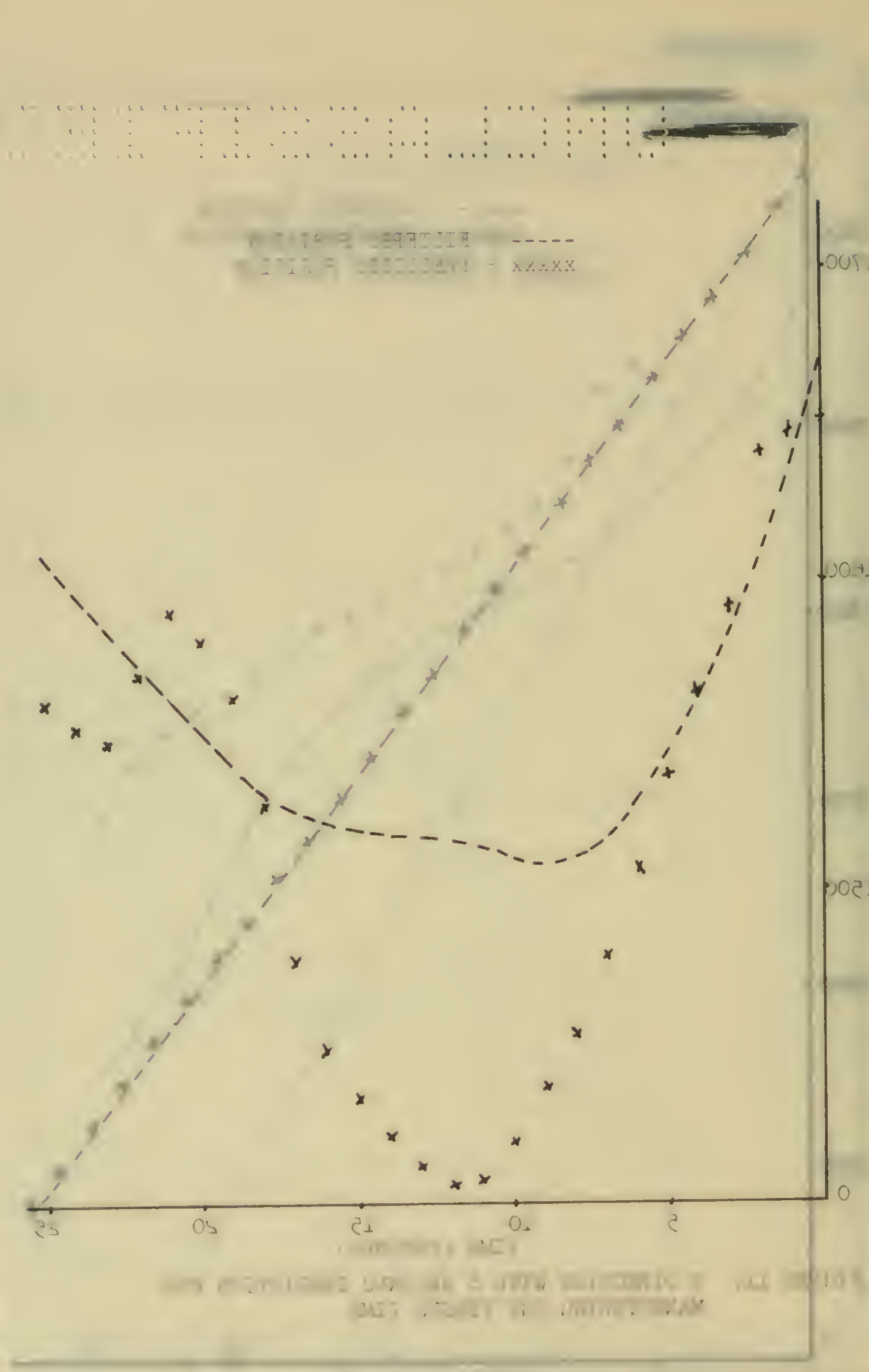
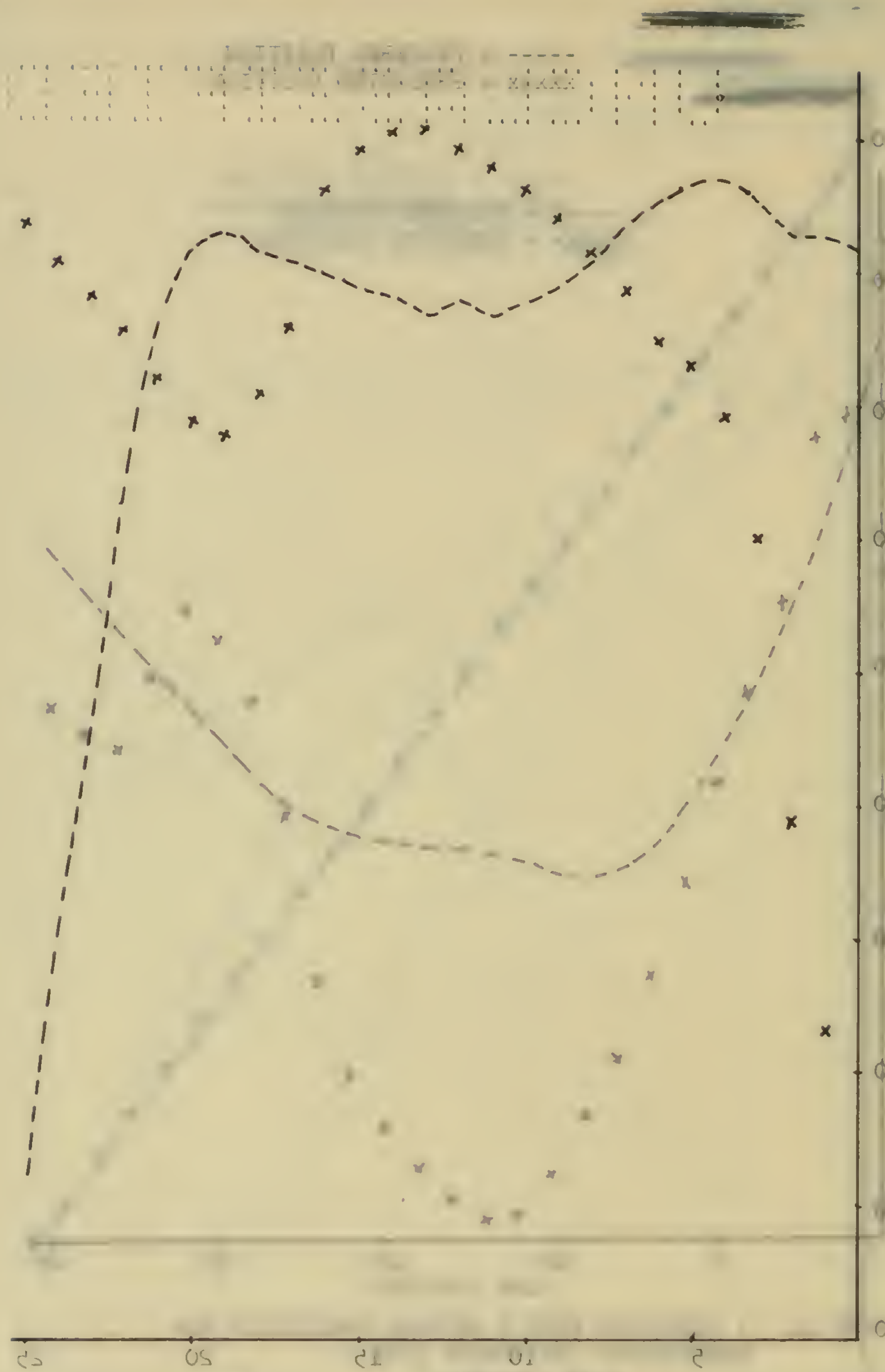


FIGURE 12 Z DIRECTION WITH 8 SECONDS PREDICTION FOR MANEUVERING TGT VERSUS TIME



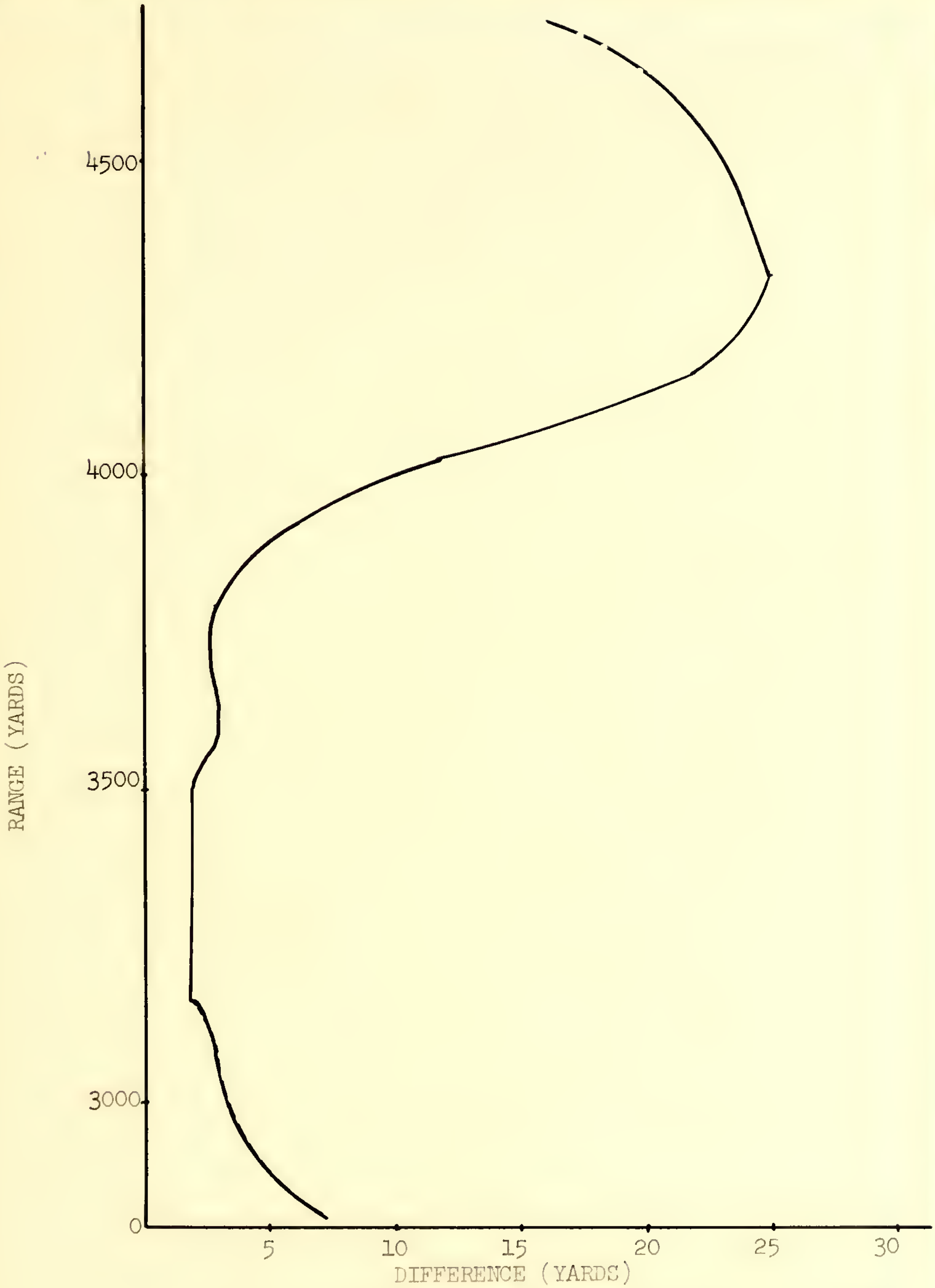


FIGURE 13. ABS DIFFERENCE BETWEEN ACTUAL X AND PREDICTED X POSITIONS FOR NON-MANEUVERING TGT VERSUS RANGE

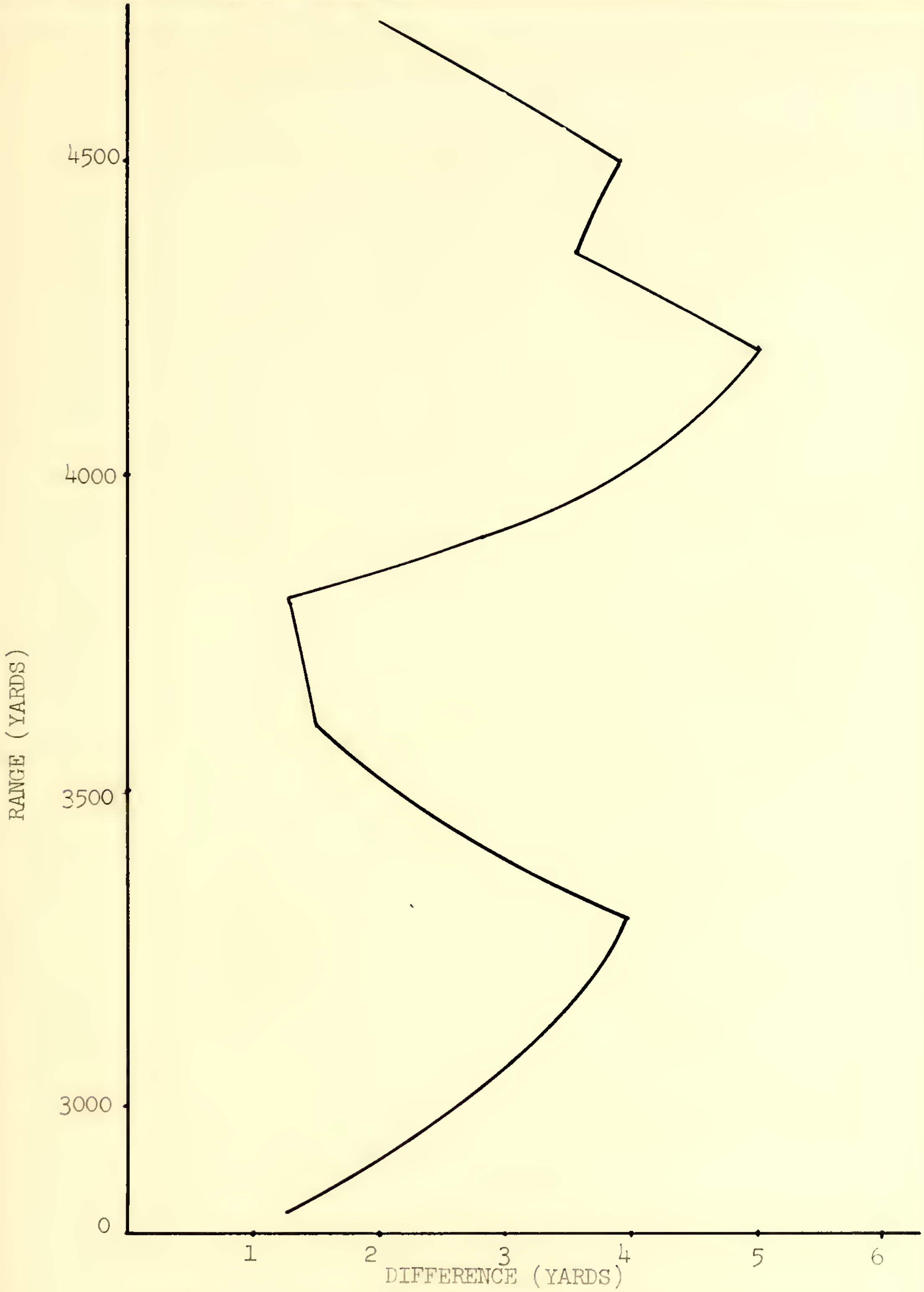
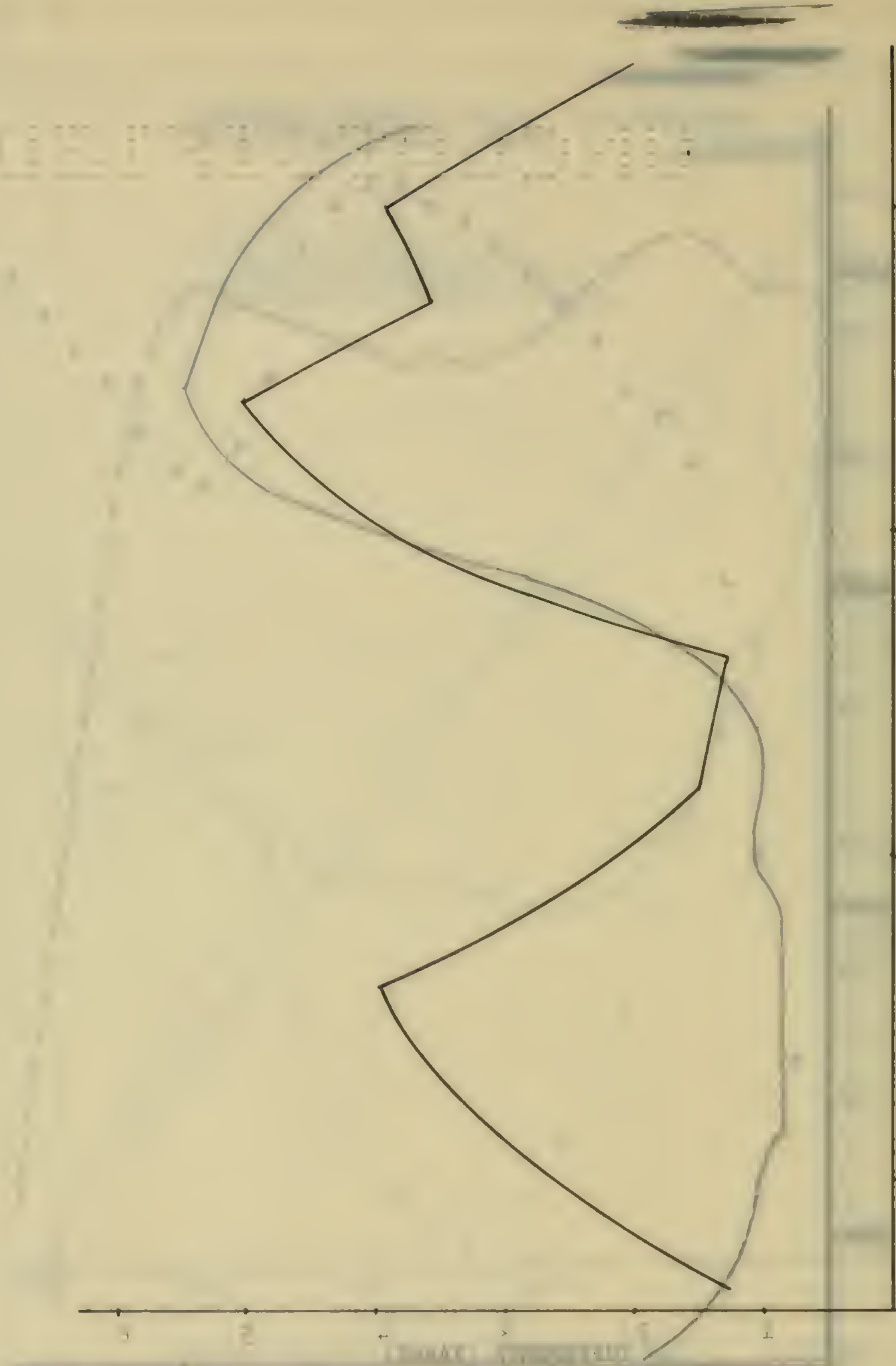


FIGURE 14. ABS DIFFERENCE BETWEEN ACTUAL Y AND PREDICTED Y POSITIONS FOR NON-MANEUVERING TGT VERSUS RANGE



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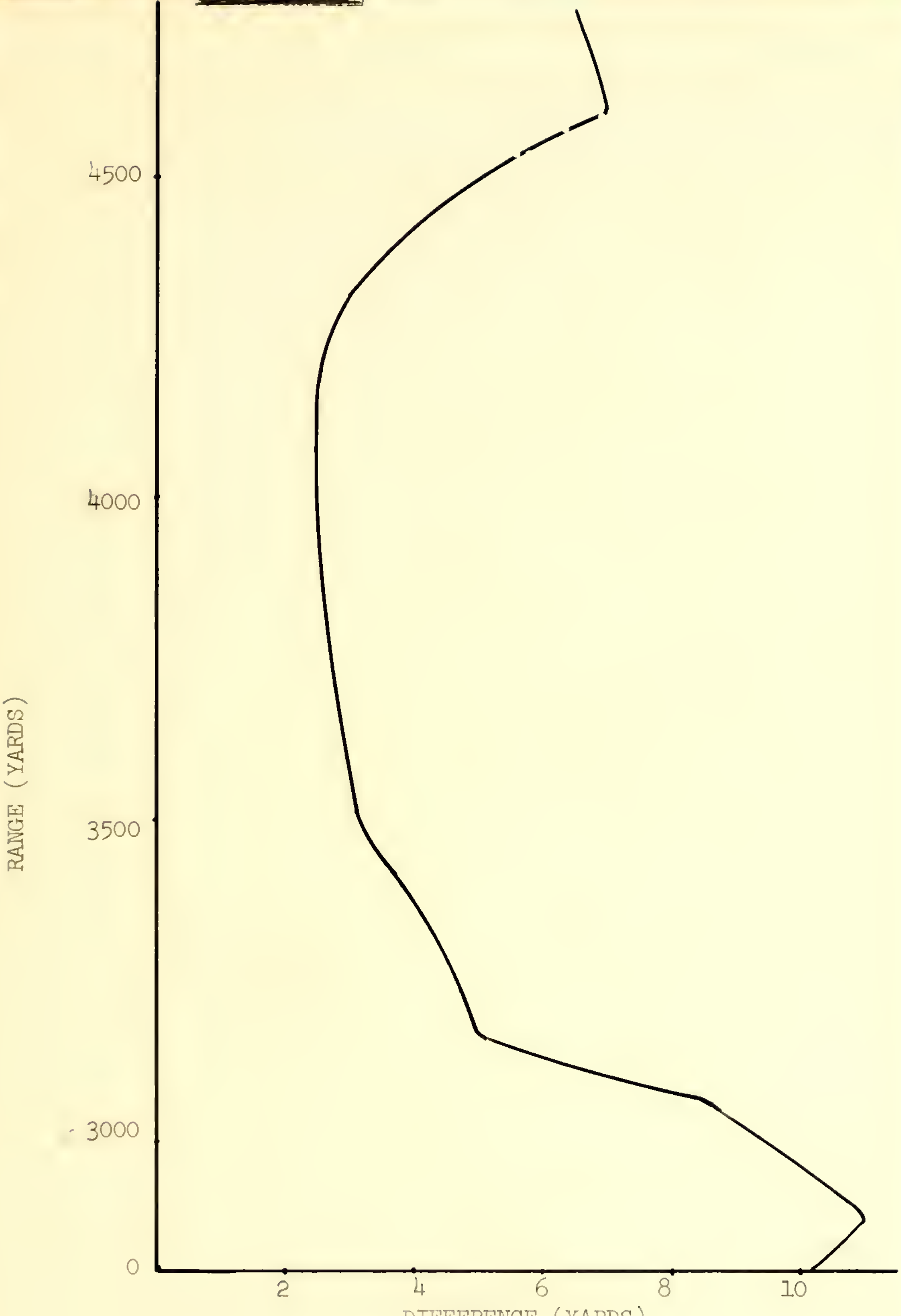

FIGURE 15. ABS DIFFERENCE BETWEEN ACTUAL Z AND PREDICTED Z POSITIONS FOR NON-MANEUVERING TGT VERSUS RANGE

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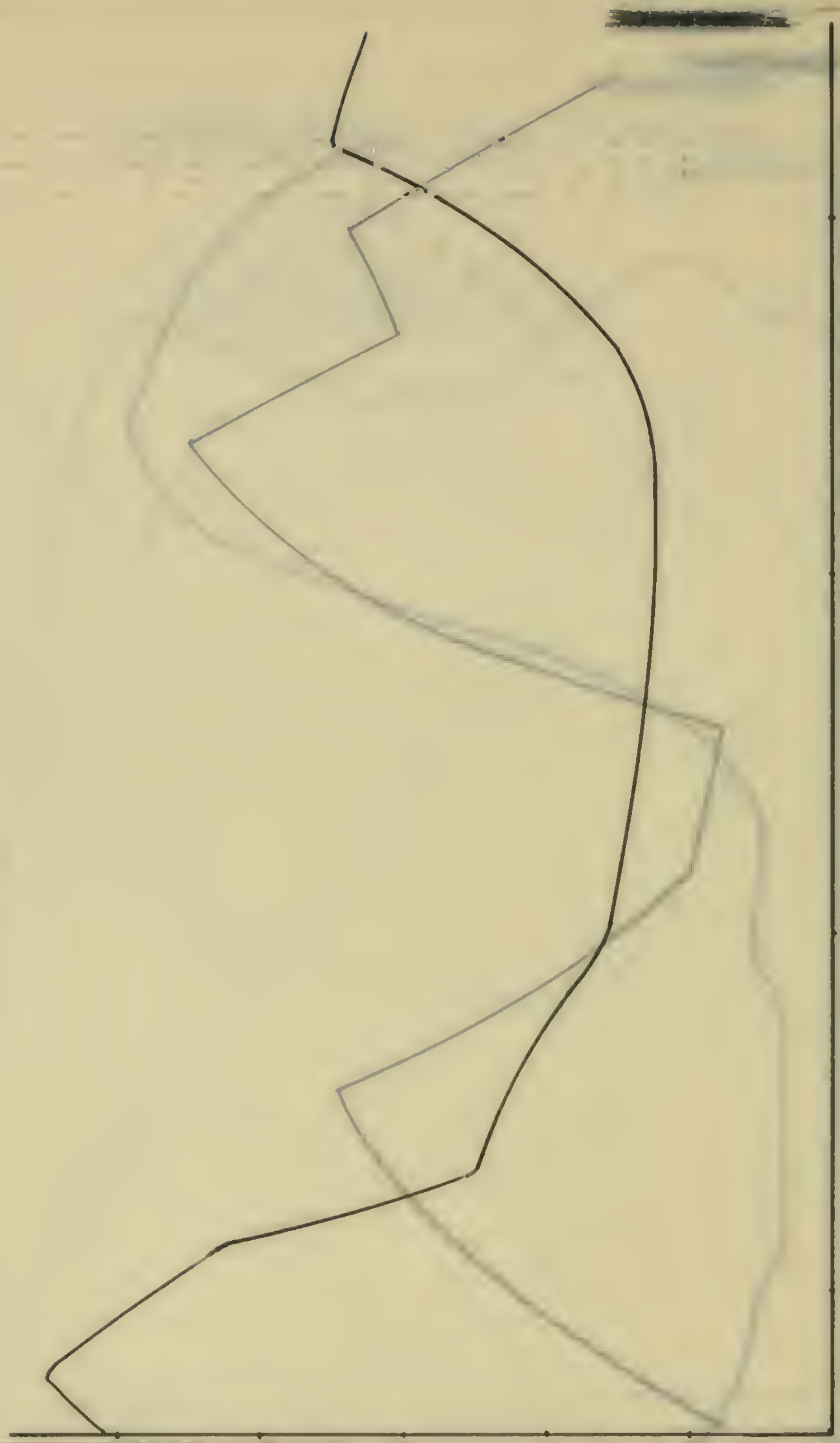

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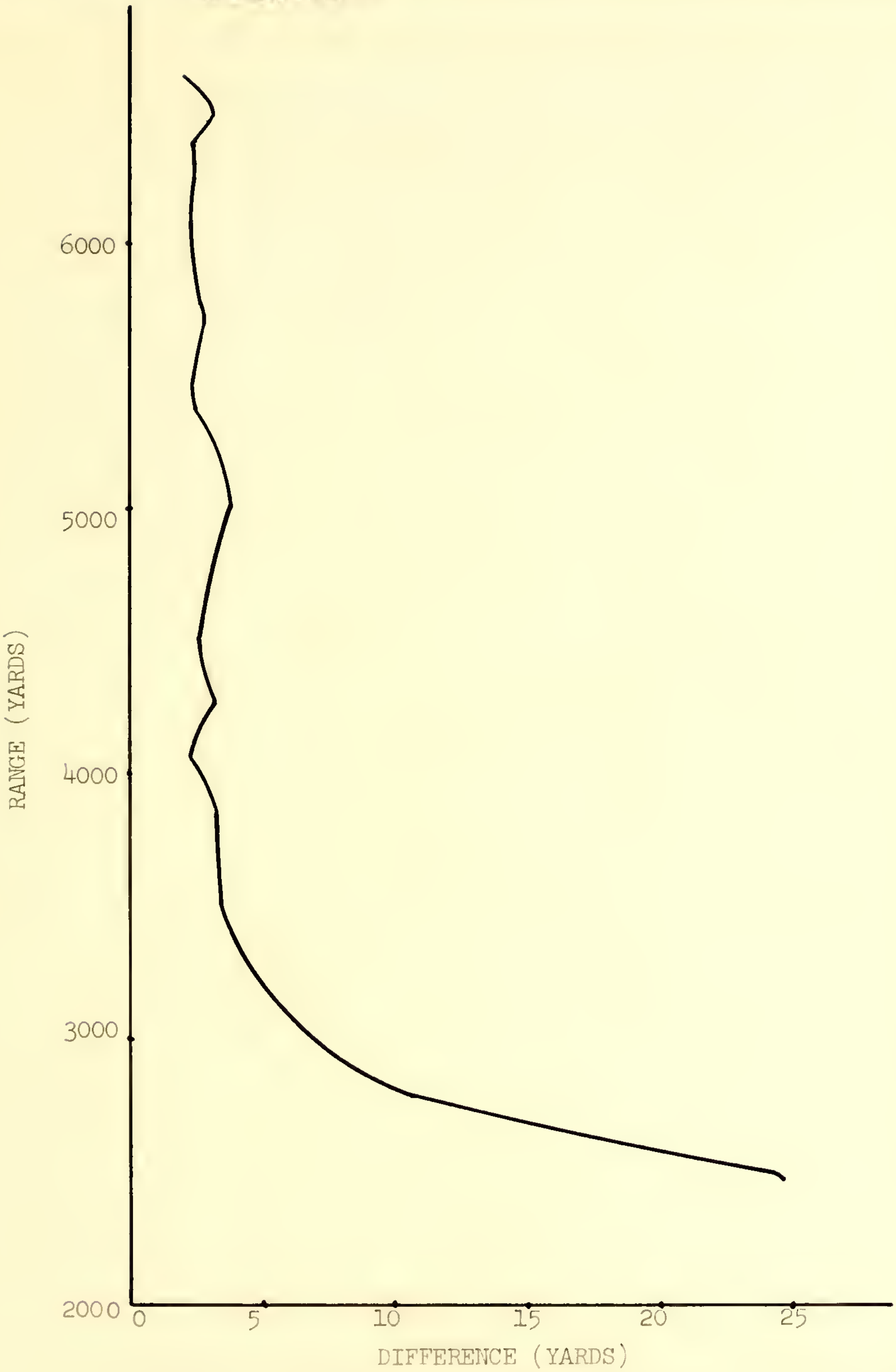
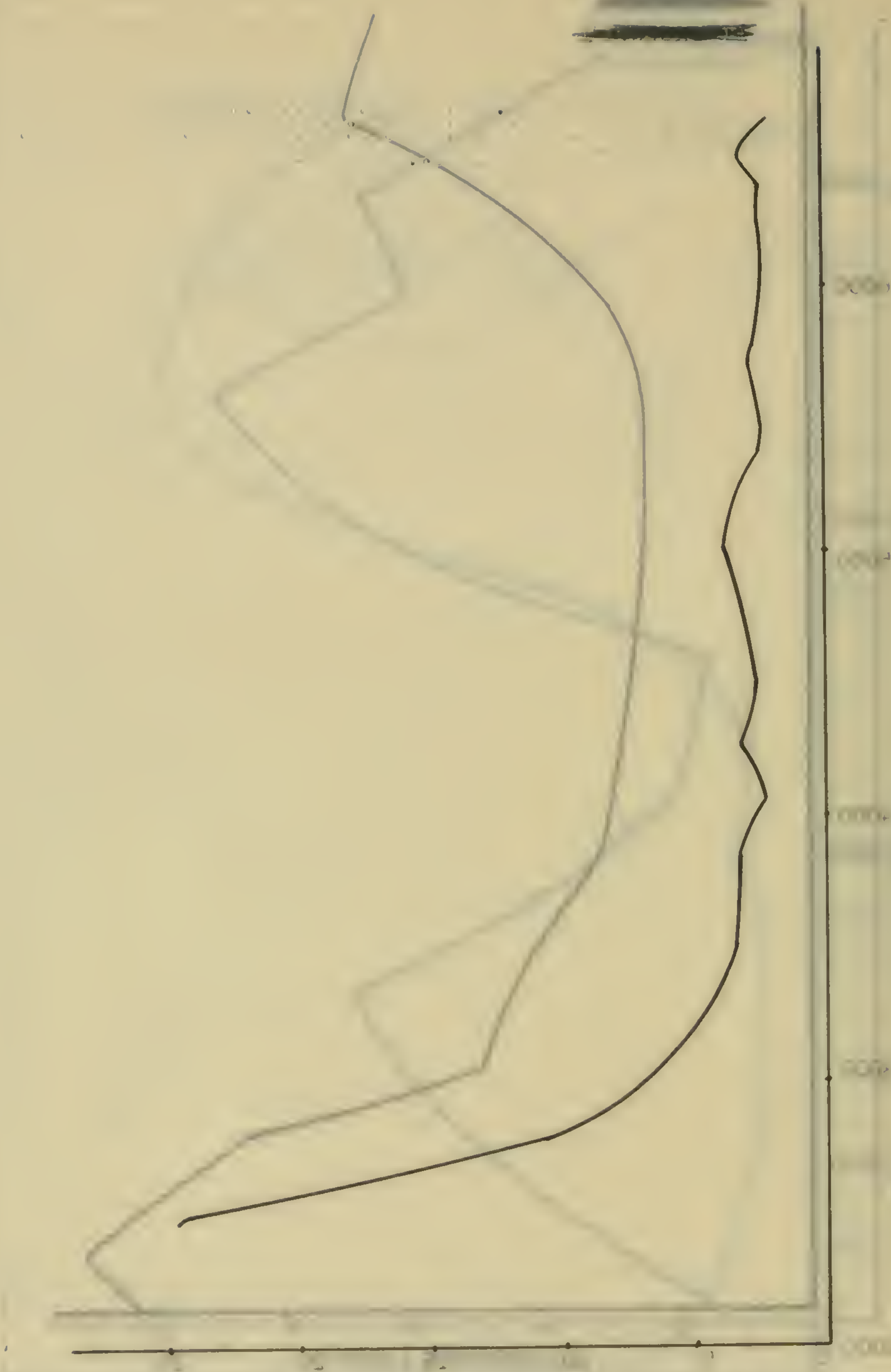


FIGURE 16. ABS DIFFERENCE BETWEEN ACTUAL X AND PREDICTED X POSITIONS FOR MANEUVERING TGT VERSUS RANGE

[redacted]



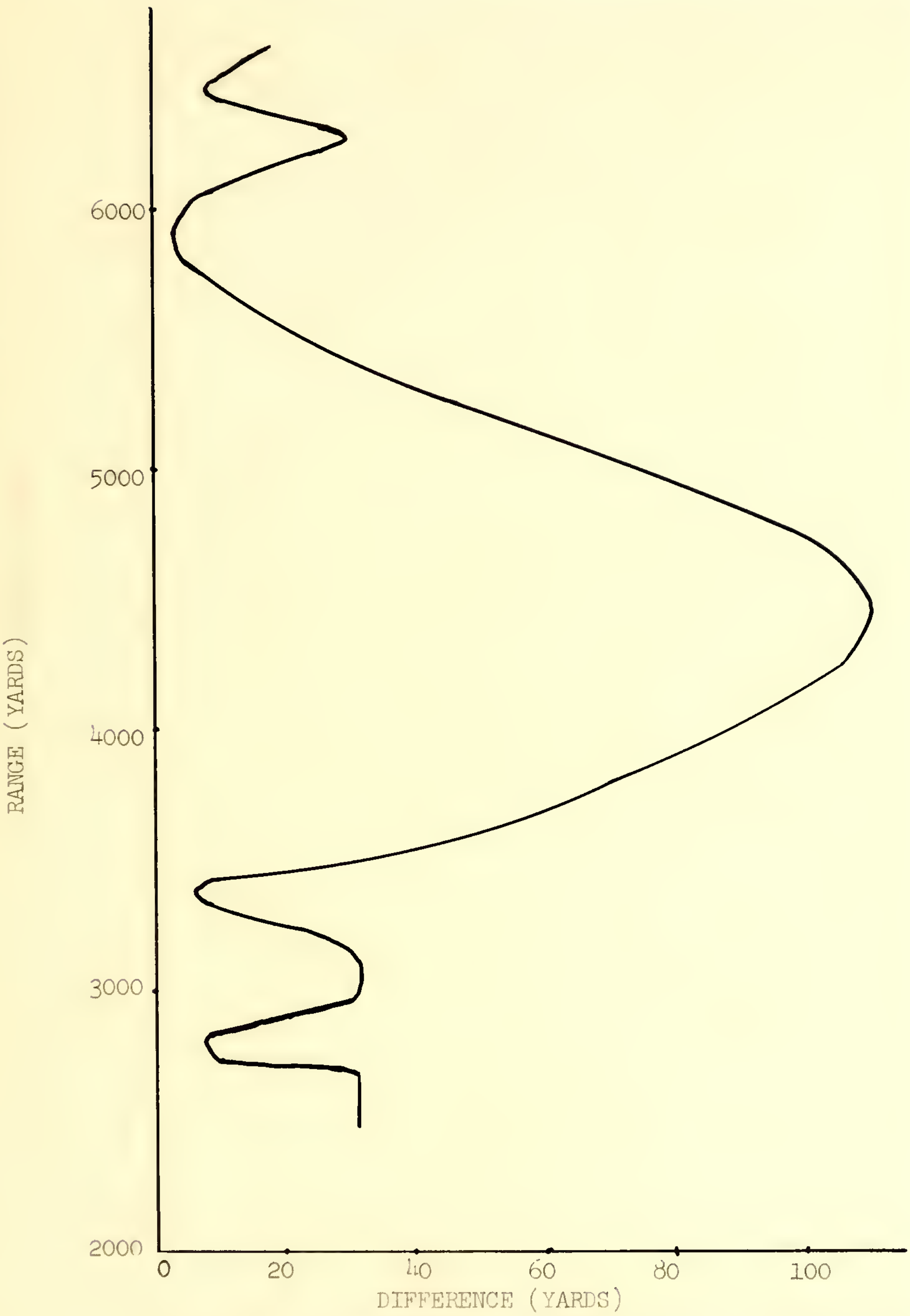


FIGURE 17. ABS DIFFERENCE BETWEEN ACTUAL Y AND PREDICTED Y POSITIONS FOR MANEUVERING TGT VERSUS RANGE

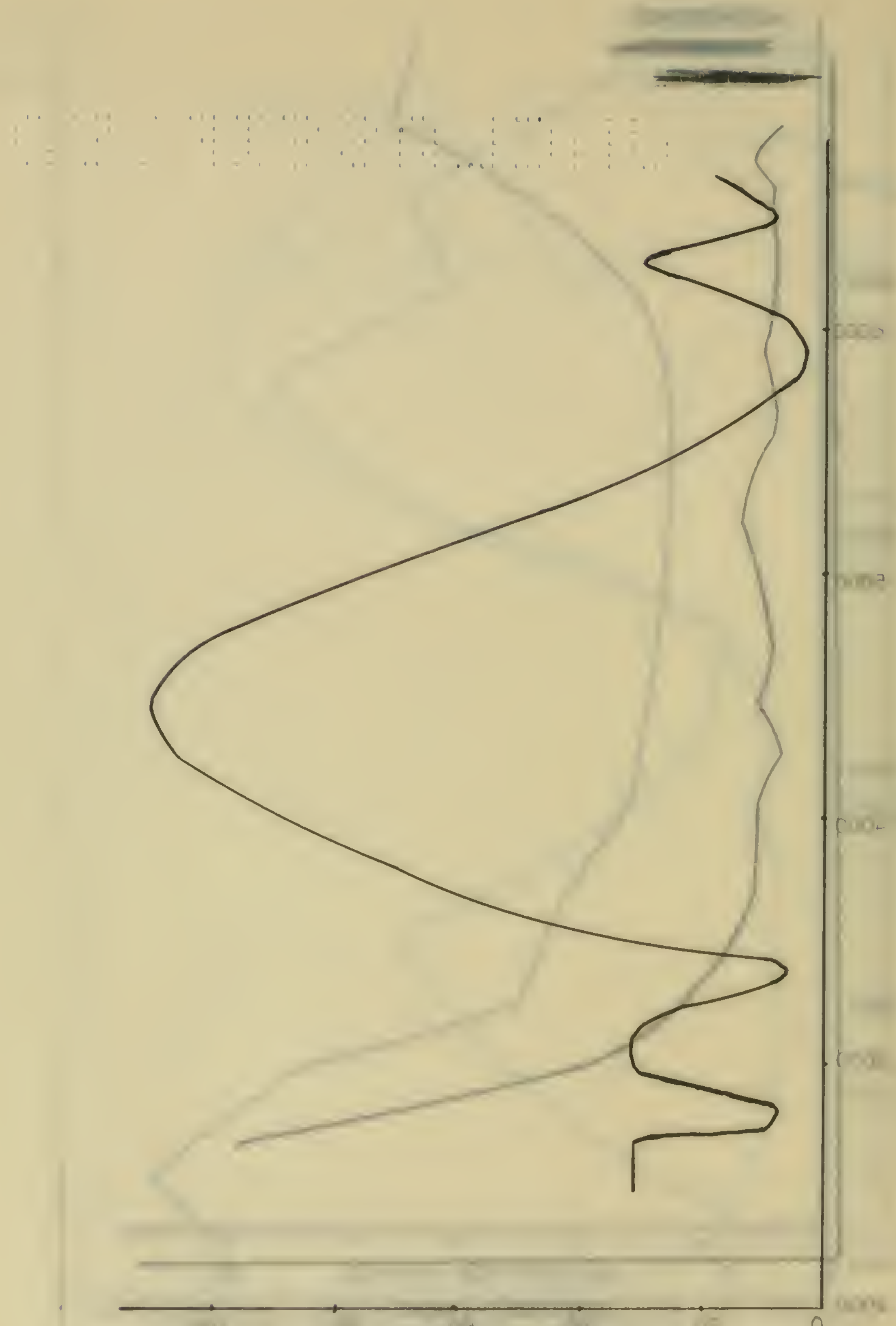
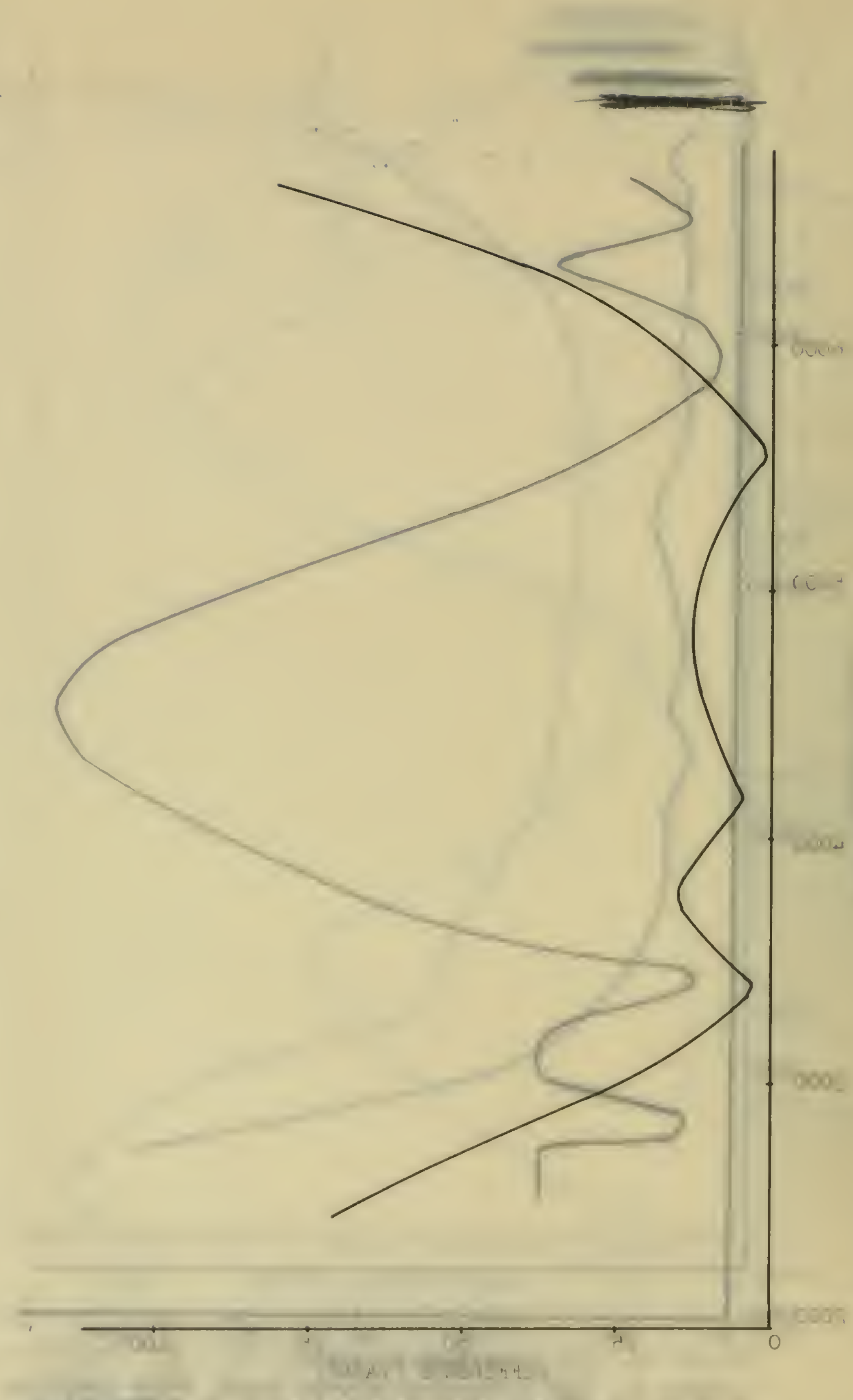


FIGURE 18. ABS DIFFERENCE BETWEEN ACTUAL Z AND PREDICTED Z POSITIONS FOR MANEUVERING TGR VERSUS RANGE



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